Documentation for SSC meeting 14-11-2011

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1. Introduction

This document aims to answer the questions posed to the KM3NeT consortium by the Scientific Standing Committee. The basis of many of the answers is contained in the technical design report [**1**]. This document gives an update to the present status of technology and physics insight. The questions will be summarized here with a short answer. Reference will be given to the relevant chapter in this document for more details.

It should be noted that all physics analysis results are produced using three separate reconstruction and simulation packages. This allows for a considerable amount of cross checking. At present the understanding of the reference detector (towers placed at distances of 180 m in two circular footprints) is good and the three analyses agree. For the other detector configurations the agreement is not yet perfect. Investigation into the differences will still take some time, but will finally improve the confidence in the results. Where relevant the uncertainties have been highlighted in the document.

The science case is presented in chapter 2, followed by the performance investigations in chapter 0. All technical and financial subjects are covered in chapter 4. The issues concerning the different sites available for the hosting of the KM3NeT detector are discussed in chapter 5. Chapter 6 finally presents the project risks. Appendices with investment cost details and risk analysis details follow at the end of the document.

Questions

Questions to KM3NeT Collaboration

1. Given that the priority is to find galactic neutrino sources, show how the design is optimized from that priority.

   Description of the optimisation procedure is given in Chapter3.1. The optimal detector is one with towers spaced at 130 m distance and a total number of 320 towers. It has a total volume of 3.5 km^3. Alternatively, 640 strings spaced at 100 m provide similar sensitivity. The optimal footprint has yet to be finalized, but first indications are that four building blocks of 80 towers or 160 strings perform identically to smaller numbers of larger blocks with the same number of detection units. Both designs utilize the multi-PMT DOM. (Chapter 3.1)

   a. Provide energy threshold and range, as well as a sensitivity plot vs. E.

   The neutrino effective area at 10 TeV is 25 m^2 for cuts optimized for maximum sensitivity to the RXJ173 flux and source size. The effective area at very high energy reaches about 1000 m^2.(Chapter 3.1)

   b. Provide example sources using a simulation based on final detector design.

   Example sources are RXJ1713.7-3496, HESS J1614-518, and RXJ0852.0-4622.

   c. For these sources, demonstrate how a significant observation can be made in a reasonable amount of time, taking into account the recent results of IceCube, gamma ray astronomy and theoretical estimations. What is the minimum size detector worth building?

If the gamma ray flux from source RXJ1713.7-3496 is fully of hadronic origin the proposed detector will produce a 5σ discovery after 6-8 years. For HESS J1614-518 10 years are required while for RXJ0852.0-4622 5 σ is reached after 7 years.(Chapter 3.2)

2. Detector design: In terms of science, cost, special conditions of deep sea deployment:
    a. Compare multiPMT to single PMT optical module (including cost, production time, reliability, performance)

Cost of 2 multi-PMT DOMs is similar to six single-PMT OMs with separate electronics container at 19k€ and 22k€ respectively. Production time is 5% less. (Chapter 4.4) Reliability is higher (Chapters 4.2 and 4.3). Performance is significantly better for photon counting. (Chapter 2.) An improvement of about 30% is expected on the basis of ongoing analysis (Chapter 3.1).

    b. Compare vertical structures (bar, string, etc.)

For equal cost the tower and string structures perform equally well for E^{-2} spectra (Chapter 0) For Galactic sources, the bar length of 6 m seems not optimal. A detector with towers with 15 m length bars at 130 m distances performs equally well to a string detector with 100 m distances. Both give an improvement of sensitivity of about a factor 2 over the 180 m tower detector.

    c. Overall geometrical configuration and prevention of blind spots

The overall geometrical configuration is driven by physics performance and the need for safe and efficient deployment. Building blocks approximately the size of an IceCube detector allow for reasonable flexibility in deployment.

    d. Readout electronics and triggering

All data to shore and online software based filtering provides the most flexible triggering and readout option. Using hits from optical modules that have one PMT hit in the fit improves the angular resolution in the critical energy regime of 1 to 100 TeV by a factor of 2. Buffering of all data for transient events allows for better sensitivity. Source following for better sensitivity is also possible in this scheme. (See chapter 2)

3. Highlight the advantages of KM3Net compared to IceCube

The sky coverage contains all but a few of Galactic sources, observed by HESS. IceCube sees only a few with a similar energy threshold. KM3NeT is 4 times larger than IceCube. The angular resolution is significantly better. (Chapter 3.6)

    a. Compare the use of high energy showers vs. muons.

For Galactic sources the shower events will contribute negligibly to the sensitivity. Therefore these have not been the subject of extensive studies yet.

    b. Size

Instrumented volume is 4.6 times as large.

    c. Angular resolution

The KM3NeT angular resolution versus neutrino direction is 0.25°-0.3° (median) for the RXJ1713.7-3496 flux and asymptotically 0.1°. (Chapter 3.1)

    d. E threshold and reach

The detector has the maximum counting rate for RXJ1713.7-3496 in the range 5 to 50 TeV. The triggered effective area at 1 PeV is slightly above 1700 m^2.

4. Site
    a. Quantitatively assess the three candidate sites in terms of depth, bio-fouling, bioluminescence, optical properties, distance to shore,

See Chapter 5.

    b. Design the optimal detector for the best site.

The detector described in the answer to questions 1 and 2 gives optimal results in all three sites. The effect of the atmospheric muon background at angles up to 15 degrees is being investigated. The required number of simulated background events is very large and being produced.

    c. Quantify the impact on the main science goal, construction and operation costs of using one, two or three sites, using optimized designs for both single and multiple site solutions at fixed total cost, considering both neutrino-induced shower and muon signals.

There is no impact on the main science goal of maximum sensitivity to Galactic neutrino sources. (Chapter 3.5). In single a site there will already be a separation into several independent parts, including shore cables. One, two or three shore stations have to be available. Operationally, the stations must be manned with some local personnel. The impact on running costs is 1M€ per extra site (Chapter 5).

    d. Are there other ways to use separate sites that do not require splitting the detector itself?

No. (Chapter 5.4)

5. Evaluate the project risk using the formalism described in Annex 1-KM3Net-PP-212525 (B.3.2)

See Chapter 6.

Additional questions

KM3NET-PP-SSC. Detailed questions to the KM3NET-PP collaboration for the 3rd meeting

- Provide justifications of the multi-pm choice, from all the relevant aspects: scientific, technical, economical, robustness, etc.

  Purity for photon counting is significantly higher for the multi-PMT DOM than for the single-PMT OM. The tubes have high quantum efficiency and collection efficiency. Large phototubes suffer from large after pulses that in the high rate environment of the sea cause degradation of the trigger potential. The total cost for a detector with multi-PMT DOMs is about 10% less than a solution with single-PMT OMs. The performance of the multi-PMT DOM solution is significantly better (Chapters 4.1 and 4.8).

- Provide information on the evolution of the perspectives of industrial production of the items.

  The major items that have been investigated for industrial production are the items related to the photomultipliers: the PMTs themselves, the HV boards and the concentrator rings. These are required at the level of 100000 items a year. Of the two major PMT manufacturers Hamamatsu has indicated that the level of 50000 per year is not unrealistic, ETEL will for an up front investment provide a production line capable of the required numbers. As a reference: Photonis produced 90000 similar items per year for the medical industry in the early years of this century. Other manufacturers are available. The consortium is considering multi sourcing. Moulding techniques are being investigated for the light concentrator rings. The HV boards at the level of 2500 per week are not unrealistic. Industrial assembly of the three above items is being considered.

- Give details on the multi-pm electronic R/O

  See Chapter 0

- KM3Net simulations indicate that the longer scattering lengths in seawater relative to ice will permit the reconstruction of cascade directionality well enough (a few degrees) to do pointing. This is likely one of the more compelling regions of analysis parameter space where KM3Net is intrinsically better than IceCube, and it would be important to quantify a) the predicted KM3Net directionality and energy resolutions for cascades and b) the impact of multiple sites on these quantities and the subsequent impact on, e.g., searches for point sources of neutrino-induced cascades.

  Not the present priority.

- Comparing a single site option and multi-site options and assuming a fixed total number of OMs:
  - how large is the effect on effective area for muons?
    - assuming an E^{-2} neutrino spectrum
    - separately for low energy μ(1TeV) and high energy μ(100 TeV)

  See above.

  - the same for 100 TeV muons (in detector) or for an E^{-2} neutrino spectrum applying a cut on the angular accuracy of, say, 0.3°.

  The standard cut for the reconstruction for a Galactic source used in the document is 0.15°

- what is the effect on the sensitivity to an E^{-2} point sources without cut-off and with 30 TeV cut-off in neutrino energy?
- what is the effect to diffuse fluxes (muon signature)?
- the effect of three sites for **cascade** detection (ν_e and ν_τ, i.e. 2/3 of the signal) will be negative. Clear identification of isolated cascades requires veto layers from all but possibly the bottom side which shield an inner fiducial volume. The resulting question is: what is the effect to the effective volume for cascades from ν_e and ν_τ interaction (contained and well identified and reconstructed events), and to the sensitivity to diffuse extraterrestrial an E^{-2} fluxes?

Low energy showers contained in a denser core are not considered possible, mainly due to the technical difficulties of placing detection units very close together. Another issue is the fact that because of the optical background of the ^{40}K in the sea a veto is extremely difficult to implement. For cascades the emphasis will be on extremely high energies, say larger than 1 PeV, where the atmospheric backgrounds are low. These investigations are not first priority.

2. Science Case

The geographical location of KM3NeT in the Northern hemisphere makes our Galaxy its prime field of operation. One could say that investigation of possible neutrino sources in the Galaxy is the "raison d'être" of a large neutrino telescope in the Northern hemisphere. The capabilities of such a telescope will of course provide sensitivity to extragalactic sources, but at present the science priority must be the investigation of the Galaxy.

In the TDR the detector was designed as somewhat of a compromise to allow for good sensitivity to both Galactic and extragalactic sources. The performance figures of the detector have shown that the Galactic sources have definitely come within reach and optimisation of the detector for the expected energy spectrum will make it possible to see for the first time direct evidence of neutrino production. In addition the IceCube collaboration is putting more and more stringent limits on extragalactic sources in their field of view. In particular the hoped for hard Waxman-Bahcall spectrum for Gamma Ray Bursts is already being excluded by the IceCube data.

The models of potential galactic neutrino sources, in particular the shell type Supernova Remnants, Pulsar Wind Nebulae, Star Formations Regions and the dense molecular clouds related to them, are robustly constrained by TeV $\gamma-$ray observations [**2**,**3**,**4**]. A detector of the size of the proposed KM3NeT is expected to be sensitive enough to provide the first astro-physically meaningful probes of the strongest representatives of these source populations.

Among the best-bet candidates are the young shell-type supernova remnants RXJ 1713.7-4946 and RXJ 0852.0-4622. Estimates show that these objects, with energy flux comparable to the Crab flux at energy around 10 TeV, can be detected after several years of exposure if the major fraction of the gamma-ray flux is contributed by hadronic interactions. The main challenge here is that the gamma-rays from these objects can be interpreted also within leptonic (inverse Compton) models. Both, the hadronic and leptonic models have not only attractive features but also face certain difficulties.

As an example many authors claim that the gamma ray spectrum from one such object, the SNR RXJ1713.7-394.6, is explained entirely by the process of inverse Compton scattering, whereas others can fully explain the spectrum by photons from the decay of pions produced in high energy collisions of accelerated protons and interstellar medium [**5**,**6**]. Measurements from the Suzaku satellite [**5**], have constrained strongly the synchrotron radiation spectrum from accelerated electrons. Presently, the situation is such that fits to all the multi-wavelength data can accommodate both an hadronic interpretation as well as a leptonic interpretation in terms of inverse Compton scattering [**7**,**8**]. The leptonic interpretation requires an unusually low magnetic field combined with an additional component of softer electrons that are unconstrained by the Suzaku data. The hadronic model on the other hand requires an injection spectrum for the protons with an initial spectral index of around 1.7, rather than the more conventional 2.0, combined with an exponential cut-off in the 50 TeV range. This harder power law spectrum is supported by nonlinear theories of diffusive shock acceleration. Moreover, even in the case of acceleration spectra of protons with $\gamma>1.8$, the effects related to the propagation of protons into the dense clumps inside the shell may lead to the significant suppression of low (GeV) energy protons. The data from the FERMI-LAT telescope [**9**] can be easily accommodated in both scenarios. It seems likely that at least a substantial fraction of the gamma rays has its origin in hadronic interactions. On the other hand, as long as the leptonic models cannot be robustly rejected, the predictions on neutrino signals remain model-dependent. This makes the role of neutrino observations unique for understanding of the nature of gamma-rays from SNRs, and, in a more general context, for the solution of the long-standing problem of origin of galactic cosmic rays.

Two prominent Pulsar Wind Nebulae (PWNe), the Crab Nebula and Vela X, are believed to be powered by the electron-positron pulsar winds, but one cannot exclude the large content in these nebula of protons and nuclei. This is the case for Vela X with the energy spectral distribution which peaks at 10 TeV. Remarkably, the TeV neutrino flux expected within this hadronic scenario of production of gamma-rays in this source could be detectable by KM3NeT which makes the Vela X an excellent candidate to be investigated.

Finally, because of strong internal absorption of TeV γ -rays, detectable neutrino fluxes from (somewhat fainter) compact TeV γ-ray emitters like the binary systems LS 5039 and LS I+61 303, are possible, and, more speculatively, from hypothetical "hidden" or "orphan" neutrino sources.

The size of the optimised detector is of the order of 4 km^3 and has a triggered neutrino effective area of about 2000 m^2 at the largest energies. The sensitivity is approximately flat as a function of declination and so the sensitivity is “spread” over a large area of the sky. The main effect is that for extra-galactic sources the sky coverage is larger than that of IceCube by about a factor of four, but the peak sensitivity is only marginally better. This holds for constant as well as for variable sources such as Gamma-ray Bursts.

3. Science Performance

In the TDR the optimisation of the detector was done using a E^{-2} energy spectrum. This resulted in a detector with an inter tower spacing of 180 m or alternatively an inter string distance of 130 m. Both these detectors perform well at large energies but compromise the lower energies. The Galactic sources produce relatively hard spectra, but are cut off at energies between 10 and 50 TeV.

In order to optimize the detector for these cut off spectra the source RXJ1713.7-3946 was chosen as a test case. This source lies in a region where the visibility of the source is high (~75%) and it has a large intensity, but a relatively large size with a complex morphology. It is at present is the best measured super nova remnant in gamma ray astronomy.

For the optimisation the source was simulated as a neutrino emitting disk of 0.65° extension (cone half-angle). The energy spectrum, which is suppressed significantly at energies above 10 TeV was parameterized as:

$$\Phi(E) = 1.68\ 10^{-11} (E[\text{TeV}]/1[\text{TeV}])^{-1.72} e^{-\left(\sqrt{\frac{E[\text{TeV}]}{2.1[\text{TeV}]}}\right)}\ [\text{TeV}^{-1}\ \text{cm}^{-2}\text{s}^{-1}] \qquad \textbf{(1)}$$

This spectrum is the derived neutrino spectrum assuming that the gamma ray spectrum emitted by the source is fully attributable to pion production and decay. The depletion of the flux at high energies with respect to the E^{-2} spectrum assumed in the TDR, has put a premium on the reconstruction of muons of lower energies, which in turn has an impact on the chosen density of light sensors in the detector.

The figure of merit (FoM) chosen for the optimisation was the number of years required for a 5σ discovery of the RXJ1713.7-3946 source. The 5σ discovery is defined by the probability that an upward fluctuation of background is larger than the expectation value of the signal, is less than $2.8\ 10^{-7}$. (For 3 σ the corresponding probability is 0.013)

The FoM is determined from the number of signal and background events in a search cone optimised for the detector's angular resolution. Some systematic studies, using an unbinned likelihood method and on the effect of the particular source morphology of RXJ1713.7-3946 have also been performed.

The optimisation is performed using several simulation and reconstruction programmes. A great deal of time and effort is being invested in verifying the outputs of these programmes, in order to be confident in the final result. For this procedure the data provided by the ANTARES detector have been invaluable. At present the ratio of reconstructed to triggered events for the signal is not high, around 10%. This is partly due to the harsh cuts required to remove the background. A programme of tracking optimisation using directional information of the DOM and energy reconstruction algorithms is underway and is showing very promising results.

From the start of the design study there have been two different design philosophies. Because of the complications and expense of making underwater connections one design was based on installing as many DOMs as possible on a single detection unit. To optimise information density and thereby efficiency the DOMs are spaced apart horizontally. The horizontal extent is then subject to technical constraints in terms of hydrodynamic behaviour and ease of deployment. The structure gives advantages in terms of torsional stability. The second design aimed at minimising cost of the single unit and thereby negating the cost of underwater connection. The cost has indeed been reduced significantly with respect to Antares for instance. Roughly a factor three reduction in price for an equivalent unit was obtained. The two designs that were adopted for optimisation were the following:

- A tower structure made of 20 storeys each consisting of a 6m bar with a digital optical module at either end. The bars alternate in direction from storey to storey. The distance between storeys is 40 m. A total of 320 such units can be constructed. For a source energy spectrum behaving as E^{-2} the optimal distance between units is 180 m.
- A string structure made of 20 storeys. Each storey consists of a single digital optical module only. A total of 640 units can be constructed. For the E^{-2} spectrum the optimal distance between strings is 130 m.

The technical designs as well as the cost considerations are described in chapter 4 of this document. Both designs are equivalent in price and initially have an instrumented volume of about 6 km^3 and have an equal sensitivity when optimised for an E^{-2} energy spectrum. The optimisation steps have been performed for the tower and string options separately.

The performance for these detectors is very similar and is shown in Figure 1 for the tower detector. The triggered effective area reaches 2500 m^2 asymptotically. It shows a marked decrease below 10 TeV. At 10 TeV the triggered effective area is 60 m^2.The reconstructed efficiency shows a similar but more pronounced behaviour, the equivalent numbers being 1500 m^2 and 20 m^2 at 10 TeV. The reduction at low energies is amplified even more when the cuts to optimise the discovery potential for E^{-2} point sources are applied.

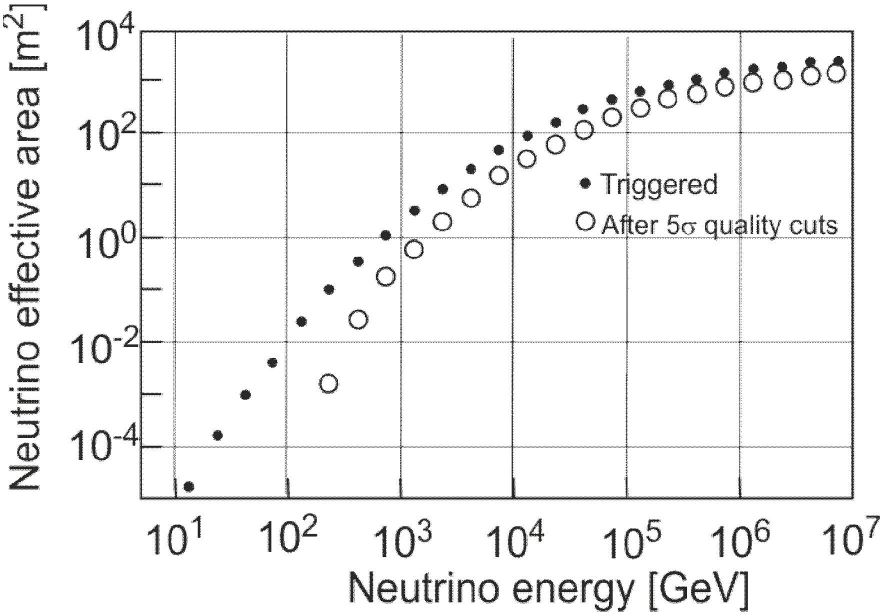

Figure 1: The effective area for the reference detector of 308 towers arranged in two separate and independent blocks of 154 units. The inter tower distance is 180 m. The three different curves indicate the triggered neutrino effective area, the reconstructed neutrino effective area. Finally the effective area after cuts for optimising sensitivity for an E^{-2} energy spectrum produced in a pointlike source.

For cuts optimised for the discovery potential of RXJ1713.7-3496 the number of signal events per year is 3.2, the number of background events is 4.1 and the FoM of this detector is 12-14 years. This has been determined for three different simulation programmes and three different reconstruction programmes. Analysis (A) uses a simulation derived from the IceCube simulation package, simulation (B) uses the KM3 simulation programme presently used in Antares and analysis (C) uses a GEANT4 based simulation. For the reconstruction analysis (A) uses a general reconstruction package based on maximum likelihood with the starting direction determined from prefits to clusters of transversely causal hits starting in several hundred predetermined directions, (B) uses a similar programme but uses the direction of the source as the direction of a prefit before a somewhat different maximum likelihood reconstruction and analysis (C) uses a χ^2 based Kalman filter algorithm.

For the string detector with 130 m spacing the equivalent numbers of 3.2 (signal), 3.4 (background) and 10 years obtained using the method (A) and 2.7 (signal), 2.2 (background) and 10 years FoM with method (B). It should be noted that the error on the FoM is typically ±1 year.

	Signal [year^{-1}]	Background [year^{-1}]	FoM
A	3.2	4.1	12.5
B	3.2	4.1	12.5
C	2.9	4.0	13.9

Table 1: Number of events per year in background and signal from RXJ1713.7-3496 for the three different combinations of simulation and reconstruction programmes.

For the analysis (C) also an energy dependent reconstruction algorithm has been used that improves the FoM by about 25%. This method is still being perfected.

A disadvantage of the, on average, lower energies from the Galactic sources is the fact that the angle between neutrino and muon in the charged current interaction becomes non negligible and the excellent angular resolution of the KM3NeT detector cannot be exploited fully. Similarly the extension of most galactic sources has a negative influence on the discovery potential. It is clear that this detector does not provide a satisfactory signal from Galactic sources.

Given the flux from RXJ1713.7-3496 convoluted with the triggered effective area, around 30 events per year pass the trigger, for the background events we expect around 100 events emanating from the source disk. To optimise the signal to noise ratio quite strict cuts are necessary. Typically they reduce the number of signal events by a factor of 10 while reducing the background by a factor 25.

The major difference between signal and background is concentrated at low energies. This means that to optimise the background suppression an accurate determination of the energy of the track is required. Therefore a denser and more independent sampling of the energy loss along the track is required. This can be obtained by placing the units closer together (providing more samplings per unit track length) but also in the case of towers increasing the bar length (more independent samplings).

3.1 Optimisation

A systematic study is ongoing to determine the optimal detector layout for galactic sources, i.e. RXJ1713.7-3496. Presently the FoM has improved significantly from the 12.5 years obtained previously to a FoM of 7-8 years when reducing the distance between detection units to between 100 and 130 m in the case of towers and 80 to 100 m in the case of strings. The numbers of signal events vary from 3-5 events and the background is at the 2-6 event level. The angular resolution with respect to the neutrino direction for the different detectors and reconstruction algorithms ranges from 0.25° to 0.3° depending on the applied cuts (see for instance Figure 2).

One issue encountered is the fact that, whereas the three different simulation and tracking programmes agreed remarkably well at 180 m distance, they begin to deviate at the 10-20% level at the shorter distances. This shows up as a significant variation in the efficiency for signal and background, although these efficiencies are correlated. This is presently being investigated. The three prong attack that is being used to investigate the programmes has already provided insights into for instance the differences in the performance of the simulation programmes and has led to a move toward full photon tracking simulations. This work is being done in cooperation with the IceCube collaboration.

Despite the differences, all analyses show a marked improvement of the figure of merit when decreasing the distance between detection units. It should be noted that the reduction of the distance between detection units has an impact on the design of detection units, the deployment strategy and the layout of the seafloor network. These issues still need to be addressed, but do not seem insurmountable.

For the near future the understanding of the differences between the different reconstruction strategies is crucial and will provide the stepping stone toward more efficient algorithms. This is an ongoing process. The influence of an efficient energy estimator is being investigated and already improves the FoM by 20% in one of the reconstruction algorithms. Including the directional information of the source in the reconstruction procedure as in reconstruction (B) seems to have a significant impact on the results. The exact size of the impact is being investigated.

For the 130 m detector an investigation into the length of the bar has been performed. Two longer lengths have been studied. In general the performance improves with bar length. Using the single analysis (B) the effects are summarised in Table 2. As a comparison the performance of a string detector with 100 m inter string distance using the same analysis is also given in the table. In general distributing the optical modules more evenly over the detection volume leads to a better performance. Similar results are obtained with analysis (A) be it with a FoM about 1.5 year longer.

	Distance	**Bar length**	**Years 5s %**	**N_{source} $[year]^{-1}$**	**N_{back} $[year]^{-1}$**
Tower	130	6 m	8.0	2.7	1.6
Tower	130	10 m	6.9	3.5	2.5
Tower	130	15 m	6.2	2.5	0.9
Tower	100	6 m	7.0	3.2	2.0
String	100	-	6.2	3.6	2.3

Table 2: Effect of bar length on the FoM. The performance improves as the bar length increases. For comparison the string detector with 100 m string distance analysed with the same simulation and reconstruction is shown.

Another effect that could influence the sensitivity to Galactic sources is the position in the sky. RXJ1713.7-3496 passes above the horizon for about 5 hours a day and reaches to 15° above. Investigations are underway to determine if the background is still manageable when reconstruction is attempted above the horizon. Antares has shown that up to 5° is possible. Such an investigation requires a huge sample of simulated atmospheric muons. The production is of these is presently underway. Assuming the full 15° can be reached a further improvement of about 20% can possibly be obtained in the FoM.

Performing an unbinned maximum likelihood analysis as opposed to a simple binned method also, from experience with Antares and IceCube, improves the FoM by around 20%. Combining this method with the morphology of the RXJ1713.7-3496 source yields a further 15%.

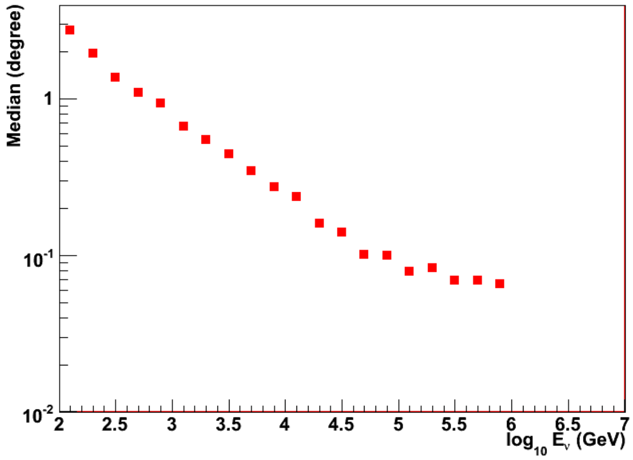

Figure 2: Median angular distance between the generated neutrino direction and reconstructed as a function of the neutrino energy. The cuts of the discovery (5 σ 50 %) are applied.

3.2 Other Galactic sources

The optimisation is taking place using the RXJ1713.7-3496 flux and morphology. A few other sources have also been considered as candidates as neutrino sources. One other source is a super nova remnant and two belong to the category of HESS sources without or with ambiguous counterparts.

The FoM has been determined for these sources using reconstruction (A) and the smaller detection unit distance. The results are given in Table 3. For comparison analysis (B) yields 6.0 years for RXJ1713.7-3496. It is interesting to note that the larger source RXJ0852.0-4622 in fact gives the shortest discovery time. For the larger sources an analysis taking into account their morphology is being undertaken.

Source	Radius [degree]	N_{signal} [year]$^{-1}$	$N_{background}$ [year]$^{-1}$	FoM [year]
HESSJ1616-508	0.16	2.0	1.8	15.5
HESSJ1614-518	0.21	2.8	4	10
RXJ1713.7-3496	0.65	4.7	5.9	8.5
RXJ0852.0-4622	0.90	7.1	11.8	7

Table 3: Details of four galactic sources that are potential neutrino candidates.

3.3 Fermi bubbles

Recently the data from the Fermi satellite has revealed a peculiar structure emitting gamma rays [**10**]. The structure has the shape of two large “bubbles” one above the centre of the galactic plane and one below. The origin of these structures is subject of speculation, but one model attributes the gamma rays to a hadronic production and therefore predicts a significant neutrino flux to be emitted [**11**]. The expected signal in the KM3NeT detector has been simulated in the framework of this model. Figure 3 shows the 3 and 5 σ flux sensitivity of KM3NeT as a function of the number of years of observation for a spectrum behaving purely as E^{-2}, and for one cut-off exponentially at 100 TeV. The predicted intensity from the model gives a 5 σ signal after about one year.

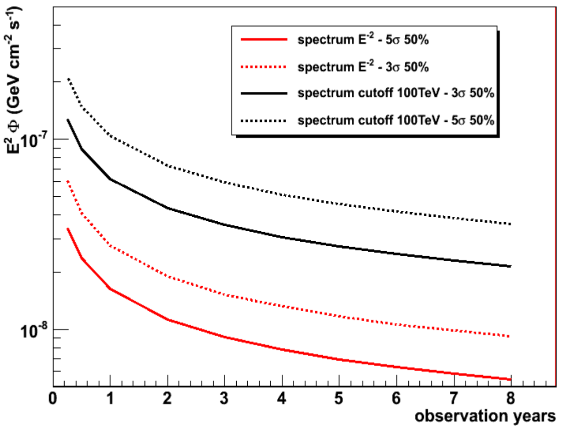

Figure 3: the 3 and 5 σ flux sensitivity for Fermi bubbles versus the number of years of observation. The estimates are shown for a pure E^{-2} spectrum (red) and a spectrum cut off at 100 TeV (black). The Flux predicted in [11] is at the 10^{-7} scale in this figure.

3.4 Impact on other physics

Figure 4 shows the ratio of the effective areas of a 130 m tower detector and 180 m tower detector as a function of energy. The results are given for cuts optimised for the galactic source energy distribution and at the trigger level. The effective area at higher energies is reduced by about 20% and at lower energy especially the optimised effective area improves significantly.

The sensitivity to sources with an E^{-2} energy spectrum is reduced by around 10% (depending on the reconstruction). For gamma ray bursts the reduction factor is larger assuming the harder Waxman-Bahcall spectrum, although this spectrum seems to be less favoured by the recent IceCube measurements. For such sources KM3NeT is complimentary to IceCube increasing the sky coverage significantly and the absolute sensitivity by more than a factor of two.

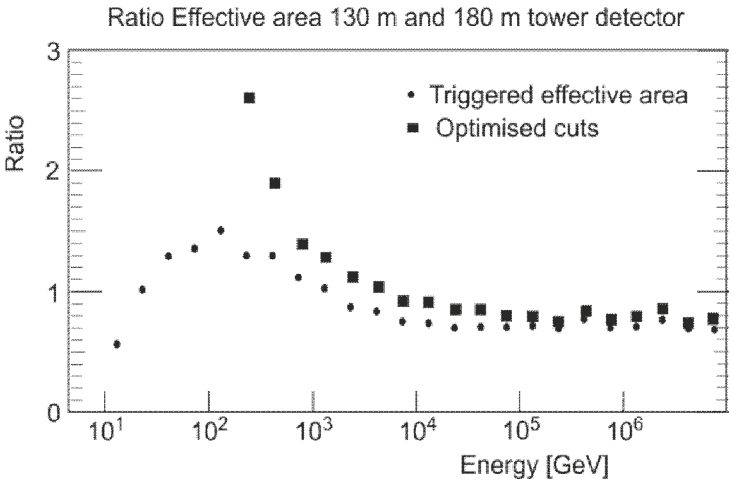

Figure 4: Ratio of the effective areas of 130 m tower detector and 180 m tower detector. Circles are for triggered effective area and squares are for effective area with optimized cuts for Galactic sources.

Cascades

In the vast majority of neutrino reactions, a hadronic cascade of typically 5-20 m length is produced along with the final-state lepton. The charged particles in this cascade emit Cherenkov light with an intensity proportional to the cascade energy. In neutral-current reactions this is the only detectable signal, in charged-current reactions the signal of the final-state lepton is overlaid. Observing cascades in the neutrino telescope allows for detecting neutrino reactions in additional channels and to measure flavour-dependent quantities.

Initial simulation studies have been performed in the ANTARES framework, demonstrating that cascades can be detected and reconstructed with an angular resolution of roughly 5-10 degrees (median) and a rather precise determination of the cascade energy. Such studies, however, require restrictive selection cuts, in particular on the position of the interaction vertex.

Given the above characteristics, the main physics objectives of cascade investigations are the measurement of diffuse neutrino fluxes at very high energies or flavour-dependent studies, mostly for oscillation analyses at low energies. Both topics are not in the core of the KM3NeT physics case and are not used in the detector optimisation process. Therefore, the use of cascades, even though being on the to-do-list, has so far not been investigated in detail. Rough estimates can however be given at present.

For high energy contained showers from GZK neutrinos the variation is a factor of 1.9. For this particular source of neutrinos the predictions extracted from the Auger high energy cosmic ray spectrum under different assumptions for chemical composition and source distribution are 0.01 to 0.6 event/km^3/year with energy above 10 PeV [**12**]. The reduction of the volume from 6.9 km^3 to 3.6 km^3 therefore reduces the range of event numbers in ten years form 0.7-40 to 0.4-20. Similar numbers are estimated for the muon signal.

3.5 Effect of smaller building blocks

In the TDR the full telescope was built of two separate building blocks of 154 (320) towers (strings). The major reason for this was the realisation that the seafloor network for a full detector with twice as many units was extremely difficult to design, taking into account the required safety margins when using ROVs. Two different methods were investigated and although solutions are available, they remain challenging. This prompted an investigation into the dependence of the physics sensitivity as a function of the number of discrete sections of the telescope. This also of course gives a good indication of the impact on the physics when placing the different detector sections in different sites in the Mediterranean.

Figure 5 shows the dependence of the flux sensitivity as a function of the number of towers used in the detector. The dependence is shown separately for a detector built from 1, 2 or 3 blocks. It is clear that the three section detector performs equally or better than the two section detector.

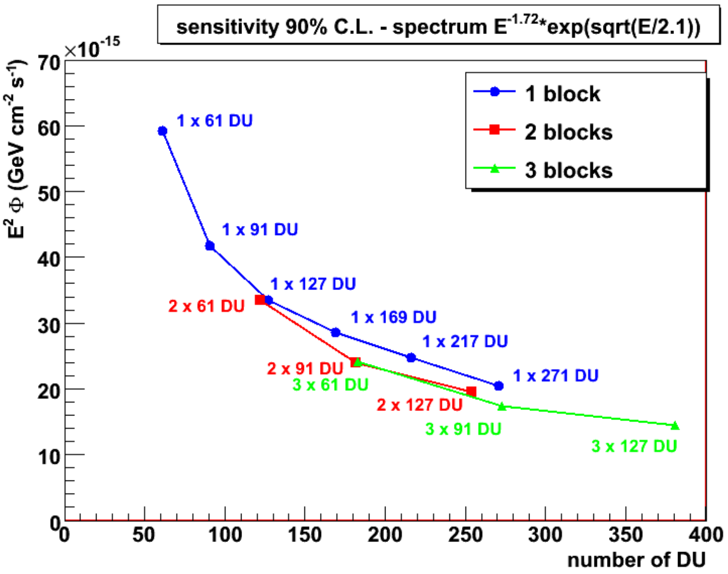

Figure 5 Sensitivity flux for a source with the RXJ1713.7-3496 spectrum as a function of the number of detection units for detector made of 1 block, 2 blocks and 3 blocks.

The investigations have been done with the different analyses and the conclusion from all analyses is similar. The splitting of the detector into more than two sections has no influence on the sensitivity of the detector if the density of photocathode area per unit volume remains the same and the section does not become smaller than about one cubic kilometre.

3.6 Comparison of the KM3NeT and IceCube potential

Field of view

The Mediterranean location of the KM3NeT telescope at a latitude λ between 36° and 43° North, allows observation of upgoing neutrinos from most of the sky (about 3.5pisr). Declinations below -90°+λ are always visible, while those above 90°-λ are never visible. Due to the rotation of the Earth, declinations between these two values are visible for part of the sidereal day. The visibility of KM3NeT (at 42°) for the Galactic centre and RXJ1713 are 68% and 78% respectively. In contrast, IceCube at the South Pole has a more restricted sky exposure (2π sr) but sees that fraction of the sky with 100% visibility. An interesting example which illustrates the advantage of the KM3NeT location is the Fermi bubbles (large 19° spherical structures extending above and below the Galactic Centre). For KM3NeT the upper/lower bubbles are visible 72%/83% of the time whereas for IceCube only ~10% of the upper bubble is visible.

The KM3NeT view of the Super-Galactic plane (75% visibility) is also enhanced compared to that provided by IceCube (55% visibility). It is worth noting that CEN-A, a well motivated potential site for cosmic ray acceleration in the Super-Galactic plane, is within the KM3NeT field of view and not that of IceCube.

The KM3NeT field of view is well matched to other the major gamma (HESS) and cosmic ray (AUGER) observatories in field and thus offers excellent opportunities for multi-messenger studies.

The excellent view of the KM3NeT for our local Galaxy makes likely the unambiguous discovery of the source(s) of the galactic cosmic rays, whether that be SNRs, microquasars, the Galactic Centre, Fermi Bubbles or cosmic ray interactions with molecular clouds around the galactic plane.

Angular Resolution

For searches of point like sources an improved angular resolution allows for an effectively reduction of the size of the search cone around the source thereby reducing the background significantly. A good angular resolution is particularly important when optimizing for a discovery rather than for setting limits. In addition, for extended sources a good angular resolution offers the potential to study the morphology of the source.

The different properties of ice and seawater have important consequences on the telescope performance. Compared to ice, the seawater is more uniform and benefits from reduced light scattering, on the other hand the sea water suffers from additional random optical backgrounds due to ^{40}K and bioluminescence. The final analysis cuts trade off angular resolution and effective area. Optimising the selection cuts for the best upper limits typically yields an asymptotic (~1 PeV) median angular resolution of 0.1°/0.6° degrees for KM3NeT/IceCube. For energies more appropriate for galactic sources (~10 TeV) the corresponding median resolutions are 0.3°/1.0°, that for KM3NeT is dominated by the muon scattering angle in the charged current interaction.

Effective Area and Energy Range

The performance of a neutrino telescope is significantly determined by the deployed photocathode area (PCA). In the following, this quantity is set into relation to the instrumented volume and the performance in form of the neutrino effective area for KM3NeT and IceCube.

IceCube has deployed 4740 10" PMTs in a volume of about 1 km^3 resulting in a PCA density of 2.1 10^6 per km^3 (as this is only an estimate, the 10" PMTs are assumed to have a flat surface). On the other hand, KM3NeT with its 308 detection units, each equipped with 20 storeys with each 2 multi PMTs, has a PCA of 1.5 10^7 cm^2. With a DU distance of 180 m the instrumented volume is 6 km^3 and, hence, the DCA density amounts to about per 2.5 10^6 km^3. One can therefore conclude that both detectors have about the same PCA density and therefore should also show similar performance per volume. As KM3NeT is significantly larger this should reflect in a correspondingly higher neutrino effective area.

At high energies where most of the detected muons are produced outside the instrumented volume, the neutrino effective area grows approximately with the physical cross section of the detector. For IceCube this effective surface area is about 1 km^2 and for KM3NeT it varies between 3.5 km^2 and 4.5 km^2 for horizontal and vertical tracks respectively. Hence, one would expect that KM3NeT has an effective area about 4 times as large as that of IceCube. Comparing the numbers for KM3NeT and IceCube [**13**]one obtains: 4 (50 m^2/12 m^2) at 10 TeV and 3.3 (1000 m^2/300 m^2) at 1 PeV which is in good agreement with the expectation.

4. Technical Detector design

The KM3NeT neutrino telescope can generally be described as a three dimensional matrix of sensors that are sensitive to the emitted Cherenkov light in the visible range. Because the attenuation length of light in the deep sea is of the order of 50-60m, at wavelengths around 470 nm, the sensor matrix can be sparse and spread out over a large volume. In designing such a detector to be placed at the bottom of an ocean there are several difficulties that must be addressed: (1) The ambient hydrostatic pressure; (2) The corrosive environment of the seawater; (3) The distance from shore for the communication; (4) The force on the structure due to the sea currents; (5) The backgrounds due to downward going muons; (6) The background dominating environment of the sea due to ^{40}K decay and bioluminescence. For the physical process of detecting neutrinos from sources near the Galactic centre there are additional requirements (a) optimal angular resolution of the reconstructed muon; combined with (b) a large sensitive area facing the Galactic centre. These issues led, during the KM3NeT design study and the Preparatory Phase, to an investigation of a few feasible designs, which have been studied in detail. In these, two different concepts can be recognised. One is to utilize tower structures placed at the seabed at large distance which have horizontal extents (bars) at regular vertical distances. The optical modules are distributed in clusters (storeys) along the vertical extent of the tower. To maximise the number of independent measurements the optical modules at each storey are separated by several metres horizontally using a mechanical support. The actual optical sensors inside the modules can be either one large (8- or 10-inch) photomultiplier tube or many small (3-inch) photomultipliers. This approach leads to an instrumented volume of one cubic kilometre for every 50 towers. In the other concept, slim string structures are placed on the seabed at smaller distances, while the photocathode area at each storey is concentrated in a single optical module using 31 three-inch photomultipliers. This approach with the optical modules more uniformly distributed in the detector volume, yields an instrumented volume of one cubic kilometre for every 100 strings.

In January 2011, the SPB of the KM3NeT Preparatory Phase project decided, as a compromise, to give priority to validation of the multi-PMT digital optical module (DOM) and the tower structure with multi-PMT optical modules at either end of a 6 m long storey and a spacing of 40m between storeys. This decision was based on a comparison of several key performance indicators. The compromise was the result of a large effort of the KM3NeT consortium to include the return of experience of the three pilot projects ANTARES, NEMO and Nestor. Since then the technical effort in the KM3NeT consortium has been directed towards the realisation and deployment of prototypes (pre-production models) of such a DOM-tower, in 2012.

The key performance indicators considered for the technical design and realisation of the KM3NeT telescope are (1) the physics performance, (2) validation of the major components, (3) validation of the assembly and integration procedures for mass production, (4) reliability estimates for a 15 year time spam and (5) estimated investment cost and assembly and integration effort.

4.1 Trigger, Readout and Data Acquisition

The readout of the KM3NeT detector is based on the “all-data-to-shore” concept. In this, all analogue signals from the photo-multiplier tubes (PMTs) that pass a preset threshold (typically 0.3 p.e.) are digitised and all digital data are sent to shore where they are processed in real time. The physics events are filtered from the background using designated software. To maintain all available information for the offline analyses, each event will contain a snapshot of all the data in the detector during the event. Different filters can be applied to the data simultaneously.

The data contain the leading edge and the time over threshold of every analogue pulse, commonly referred to as a hit. Each hit corresponds to 6-8 Bytes of data. The optical background due to decays of ^{40}K and bioluminescence amounts to typically 5 kHz for a 3 inch PMT. A reduction of the data rate by a factor of at least 10^6 is required to store the filtered data on disk. Various triggers have been developed which show a small contamination of random background. At a depth of 3.5 km, the event rate is then dominated by atmospheric muons and amounts to a few 100 Hz.

For the detection of muons and showers, the time-position correlations, that are used to filter the data, follow from causality. In the following, the level-zero filter (L0) refers to the threshold for the analogue pulses which is applied off shore. All other filtering is applied on shore. The level-one filter (L1) refers to a coincidence of two (or more) L0 hits from different PMTs in the same optical module within a fixed time window. The scattering of light in deep-sea water is such that the time window can be very small. A typical value is $\Delta T = 10$ ns. The estimated L1 rate is then about 1,000 Hz of which about 500 Hz is due to genuine coincidences from ^{40}K decays. The remaining part arises from random coincidences which can be reduced by a factor of two by making use of the known orientations of the photomultiplier tubes. For a storey with two optical modules at either end, the relatively short distance between the optical modules can be used to define a simple higher-level filter (T1). Such a T1 filter implements a coincidence of two (or more) L1 hits on the same storey within a time window of $\Delta T = 50$ ns. The estimated rate of T1s is about 0.2 Hz, primarily due to contributions from (very) low energy atmospheric muons and random coincidences. Depending on the length of the storey, genuine coincidences from ^{40}K decays may contribute as well. A simple coincidence of two (or more) T1s can be used to trigger an event.

An alternative solution to trigger an event consists of a scan of the sky combined with a directional filter. In the directional filter, the direction of the muon is assumed. For each direction, an intersection of a cylinder with the 3D array of optical modules can be considered. The diameter of this cylinder (i.e. road width) corresponds to the maximal distance travelled by the light. It can safely be set to a few times the absorption length without a significant loss of the signal. The number of photomultipliers to be considered is then reduced by a factor of 100 or more, depending on the assumed direction. Furthermore, the time window that follows from causality is reduced by a similar factor. (Only the transverse distance between PMTs need to be taken into account because the times can be corrected for the propagation of the muon.) This improves the signal-to-noise ratio (S/N) of an L1 hit by a factor of (at least) 10^4 compared to the general causality relation. With a requirement of five (or more) L1 hits, this filter shows a very small contribution of random coincidences. The field of view of the directional filter is about 10 degrees. So, a set of 200 directions is sufficient to cover the full sky. By design, this trigger can be applied to any detector configuration. Furthermore, the minimum number of L1 hits to trigger an event can be lowered for a limited number of directions. A set of astrophysical sources can thus be tracked continuously with higher detection efficiency for each source. Alternative signals with different time-position correlations, such as slow monopoles, can be searched for in parallel. It is obvious but worth noting that the number of computers and the speed of the algorithms determine the performance of the system and hence the physics output of KM3NeT.

A well know feature of photomultipliers is the presence of pre-, delayed- and after-pulses. The pre- and delayed-pulses cause a certain degradation of the timing of the signal which normally is smaller than the characteristic transition time spread (TTS) of a PMT (about 2 ns). The after-pulses are due to ionisation feedback which produces relatively large analogue pulses. These pulses mimic a signal from a nearby muon. The probability that a photo-electron triggers an after-pulse is typically 0.5-1% for a large photomultiplier (8 or 10 inch). In the presence of optical background, each photomultiplier thus produces a rate of large pulses of about 250-500 Hz. This implies that every event will be accompanied by 20-40 large pulses. This severely affects the performance of the reconstruction. This was not taken into account in the studies for the TDR. It should be noted that the segmentation of the photo-cathode area by means of relatively small PMTs is not affected by after-pulses. The number of hits, rather than total charge of an analogue pulse, yields an exact lower estimate of the number of photons that must originate from an external source. (It has been verified that the radioactivity of the glass sphere does not significantly contribute to this photon count.) As a matter of fact, the multiplicity of hits in the same optical module can be used to improve the S/N ratio of any filter. A level-two filter (L2) consisting of a coincidence of three (or more) L0 hits in a single optical module reduces the count rate by a factor of 10 compared to the L1 filter. The effect of the L2 filter on the detection efficiency of neutrinos is estimated to be less than 10%.

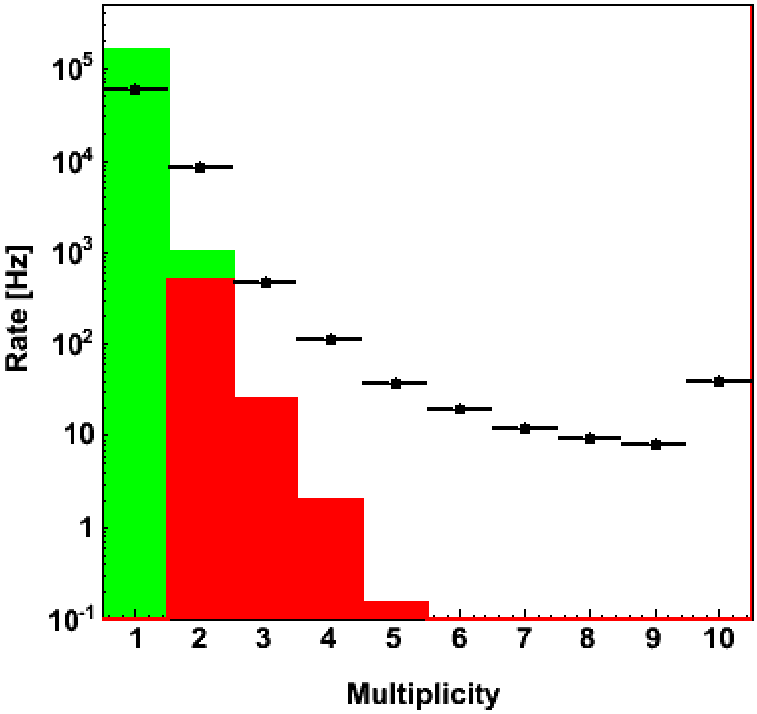

Figure 6 The count rate as a function of the number of photons. The black dots correspond to the observed rate of a single 10 inch PMT in ANTARES. In this, bin 10 corresponds to Multiplicity ≥ 10. The green (red) area corresponds to the estimated rate of accidental (genuine) coincidences due to 40K decays in a set of 31 small PMTs.

The count rate as a function of the number of photons is shown in Figure 6 for a single 10-inch PMT in ANTARES and for a set of 31 small PMTs in KM3NeT. The high rate of high-multiplicity hits observed when using a 10 inch PMT can be attributed to after-pulses. In ANTARES, there are three large PMTs on a storey. A L1 hit may be a local coincidence or a hit with a large integrated charge. In order to cope with the background, the total L1 rate should be limited to about 1 kHz or so. As a consequence, the high-threshold condition for a L1 hit is set to 3 p.e. For KM3NeT, the L1 condition is simply 2 hits. This yields a similar purity (i.e. same count rate due to optical background) but significantly better efficiency (about 85% for a 2 photon signal compared to 50% for a 3 photon signal).

The “all-data-to-shore” concept is implemented in the ANTARES telescope since 2006. The full sky is viewed with directional filters continuously. In the absence of excessive bioluminescence, a directional filter pointed to the Galactic centre is operated in parallel. This filter uses both L1 and L0 data. It has recently been shown that this filter yields a gain in the detection efficiency of neutrinos by (at least) 10%. This gain is limited by the effect of the optical background on the reconstruction which may still be improved. For KM3NeT, the estimated number of computers needed to filter the data is less than 500. The minimum number of photons to trigger an event is 8-10, depending on the filter. The chosen concept allows for a flexible, extendible, and upgradable system at a moderate fraction of the total cost (less than 10%).

Although a traditional system with a local L1 coincidence trigger at first sight may seem attractive as a tool to reduce the bandwidth to shore, it is not necessary. The currently commonly used bandwidth of optical networks provides sufficient bandwidth to sustain the expected L0-level data rate. Assuming 64 bits per recorded photon, for the envisaged photo-cathode area the total data rate amounts to about 0.2 Tb/s. This data rate to shore can be accommodated on a number of optical fibres using dense wavelength division multiplexing (DWDM) techniques. Having access to all data, the reconstruction efficiency is improved by a factor of about 1.5 at 1-10 TeV. For those events that may constitute a discovery, the availability of all data is paramount. The possibility to scrutinize the background environment, verify trigger conditions and study hit patterns in detail before claiming a discovery will be essential.

Using a passive electro-optical cable network, a point-to-point 1 Gb/s communication network will be implemented in which each optical module (or any other module) has a unique optical communication channel with the data acquisition electronics on shore. The advantage of this approach is that it minimizes the amount of active off-shore electronics – more prone to failure than passive electronics - while providing a dedicated wide-bandwidth. It allows for staged deployment of the detection units and future upgrades of the components on shore are possible during the lifetime of the detector. The use of a passive network in the deep sea and the possibility to perform maintenance of the equipment on shore not only strongly enhances the system reliability but also reduces cost and power consumption.

In Figure 8 the main functions of the readout architecture are presented. The DAQ system is based on a FPGA with an embedded processor inside the optical module (see Figure 9). The central electronics can be viewed as a hub which gathers all the information produced in the module and transmits them to shore through the assigned DWDM channel; in the opposite direction, the information received from shore (mainly slow control commands) are used to manage the functions of the optical module. The downstream data from shore consists of a Continuous Wavelength (CW) signal with a superimposed data/clock signal for detector control. The upstream signal is a modulated signal containing PMT (and other sensor) data. The electrical to optical conversion is implemented by a Reflective Electro Absorption Modulator (REAM), which is a sort of a mirror which can be turned on and off, by an electrical modulating signal. It reflects the incoming wavelength: hence, just one wavelength per optical module is needed for both directions. Since event reconstruction is based on the PMT hit time, a common timing reference must be available to front end boards, to allow for detector wide synchronization. The time offset between each acquisition channel and the fixed reference must be known in order to compare hit times. In order to facilitate the clock distribution a synchronous protocol will be used: the clock is embedded in the slow control data by an on-shore transmitter in a unique bit stream. The receiver in the optical module recovers the clock and extracts the data. The recovered clock is fed to the front end electronics which can stamp the PMT hit with the common reference. In addition, using the point-to-point connection in the network to a module, a timing marker signal can be sent forth and back to measure the propagation delay with sub-nanosecond resolution. In this way, all the receivers will be synchronised by design to the on-shore time reference, which is derived from a GPS station. The high speed transmission is timed using this clock as well: the frequency for the required serializer can be synthesized by means of a phase locked loop (PLL). The synchronous command distribution is based on the same principle. To further improve the timing resolution, the phase relation between the transmitted and received clock signals is measured continuously, thus enabling tracking of changes in propagation delay due to for example a change in temperature or a change in pressure. The data in the detection unit backbone are transported via a single cable which contains one optical fibre for each storey. The number of fibres can be reduced by a factor of 2 when the (de-)multiplexer is located approximately half way along the length of the detection unit. The power conductors reside inside the same cable. At each optical module a break out extracts the required fibre and power

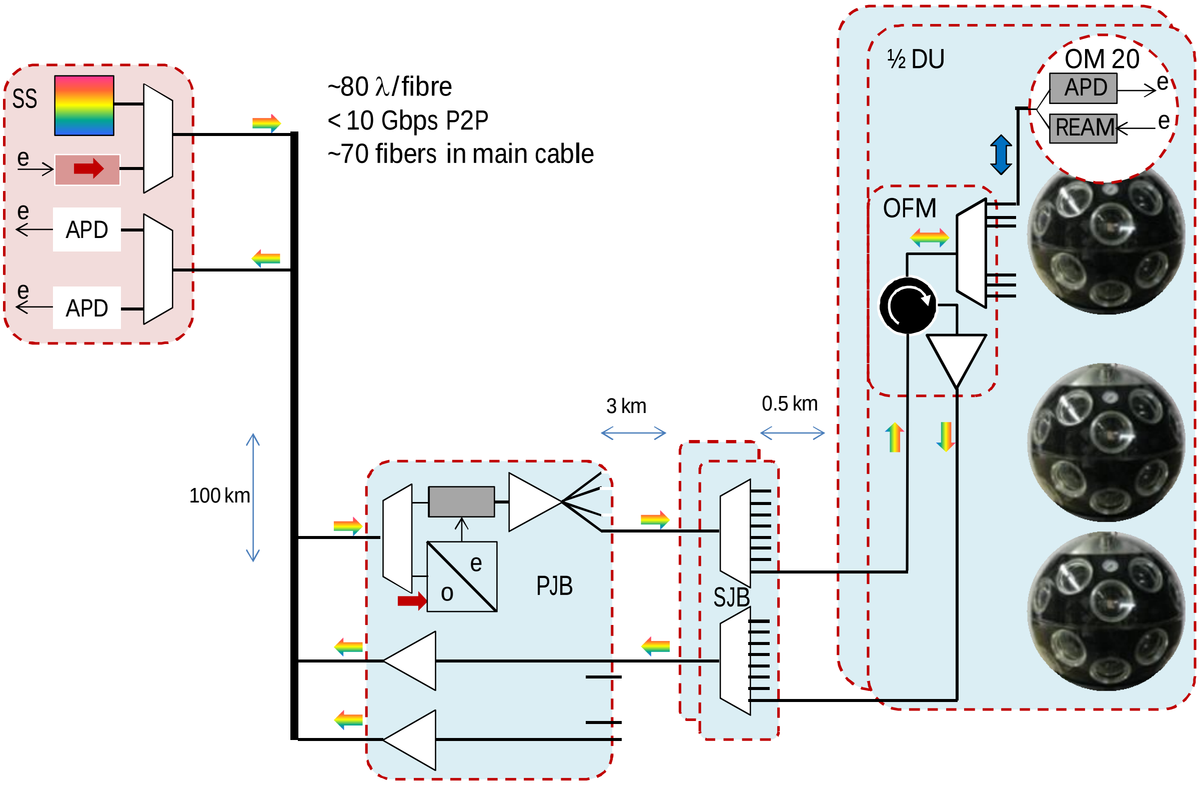

Figure 7 Scheme of the optical communication network. SS-Shore Station, PJB-Primary Junction Box, SJB-Secondary Junction Box, DU-detection unit, OFM-Optical Fanout Module, OM-Optical Module, REAM-Reflective Electro-Absorption Modulator, APD-Avalanche Photo Diode for conversion from optical to electrical domain.

wires. The multiplexing and de-multiplexing of optical signals is made inside the optical fan-out module of the detection unit. Further multiplexing of signals from different detection units is performed in the secondary junction boxes. All hardware components in the readout and data acquisition system are chosen to be standard, mass market Commercial off-the-shelf (COTS), based on server-like processors interconnected with standard 1Gbit network hardware. Exception is the reflective electro-absorption modulator (REAM). The design is 10 Gbit resistant, i.e. it is flexible enough to permit upgrade to faster processors as they become available and to migrate to a 10Gbit network should the need arise.

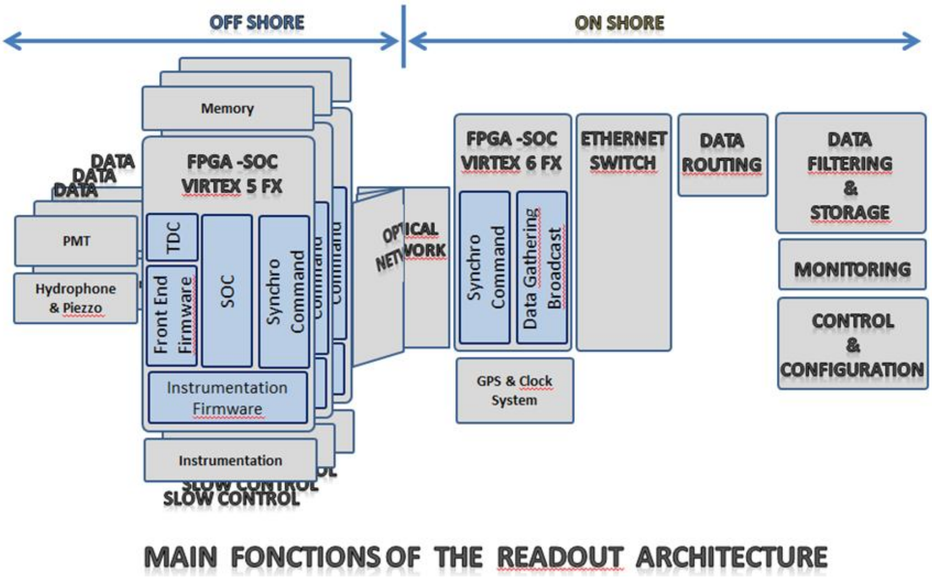

Figure 8 Readout architecture of a detector with multi-PMT optical modules.

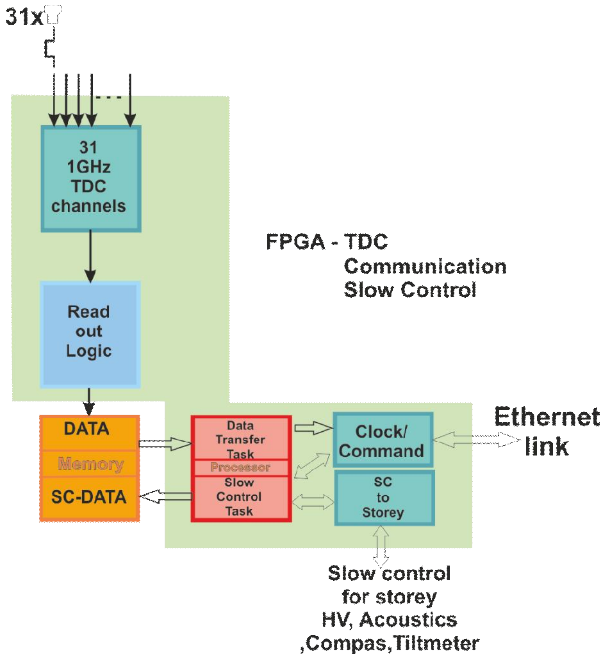

Figure 9 FPGA architecture of the central electronics of the multi-PMT optical module. The blocks in the green shaded area are implemented in a system on chip.

4.2 Multi-PMT Digital Optical Module

The design of the multi-PMT digital optical module and its product breakdown are described in detail in the technical design report. The concept for a multi-PMT optical module has been first presented to the consortium by Esso Flykt at the first VLVnT workshop in 2003 [**14**]. Following his ideas, a cost effective plug-and-play sensor module has been developed for KM3NeT with the full functionality of an ANTARES storey contained in a single pressure resistant glass sphere with a diameter of 17 inch. The module is fit to be distributed in the detection volume both in a tower configuration and in a string configuration.

The actual light sensors are 31 photo-multiplier tubes of 76 mm diameter, surrounded by a 102 mm diameter light concentrator ring. The total photocathode surface is 1260 cm^2, the total area of the three 10-inch photomultipliers at a storey of the ANTARES telescope. The photocathode area will be effectively enhanced by 20-40% by the use of a light concentrator ring, made of silicon gel and kept in place by an aluminium ring serving as a reflector. The photocathode has a concave shape in order to achieve appropriate timing resolution. The front end of the tube is convex with a radius matching the glass sphere. The length of the tube is less than 122 mm. It has a 10-stage dynode structure with a minimum gain of 10^6. The photocathode is conventional Caesium-Potassium bialkali with quantum efficiency larger than 32% at 404 nm (larger than 22% at 470 nm). The use of Caesium-Rubidium for the photocathode is no longer considered as at 470 nm the quantum efficiency is comparable to that of Caesium-Potassium, while the dark current is substantially higher. A custom low power (<45 mW) Cockcroft-Walton base provides the high voltage for the photo-multiplier tube. It includes a chip with an amplifier and discriminator, providing a LVDS signal with a length proportional to the charge. The optical module also has instrumentation that allows for the reconstruction of its position (acoustic piezo element), determination of its orientation (compass and tilt meter) and calibration of its timing (nanobeacon). The photomultiplier tubes are supported by the light concentrator rings and a foam structure. The view of the module is made as uniform as possible. The vertical orientation of the photomultipliers varies between 50 and 180 degrees with respect to a positive axis pointing upwards in vertical direction. The acoustic piezo element and the nanobeacon are glued against the glass sphere. The photomultiplier tubes are optically coupled to the glass sphere with a thin layer of optical gel. Since the sensitivity of the 3-inch photomultipliers to the Earth's magnetic field is very small magnetic shielding is not required. Segmentation of the photocathode area will aid distinguishing single photon hits from two-photon hits, which is important for the reduction of background hits from ^{40}K decay and bioluminescence in the seawater. The digitization and readout electronics is concentrated in the centre of the optical module. The central logic of the optical module is implemented using a FPGA based system. Cooling of the electronics is achieved with an aluminium mush-room shaped system that is glued to the glass sphere. Time-over-threshold values of the photomultiplier tubes are transmitted to shore via a unique optical channel using a reflective electro-absorption modulator (REAM) in the optical module and Dense Wavelength Division Multiplexing (DWDM) technologies in the optical communication network. Effectively, multiple photons in the optical module are distinguished by counting photomultiplier hits rather than determining pulse-height. Also large pulses from individual photomultipliers, e.g. due to sparking or after-pulsing, are easily recognized, as it is unlikely that this has a neutrino physics reason if only one photomultiplier will have a large pulse, while its direct neighbours have not. For timing calibration the fibre propagation delay is measured from shore using an optical 'pulse echo' technique.

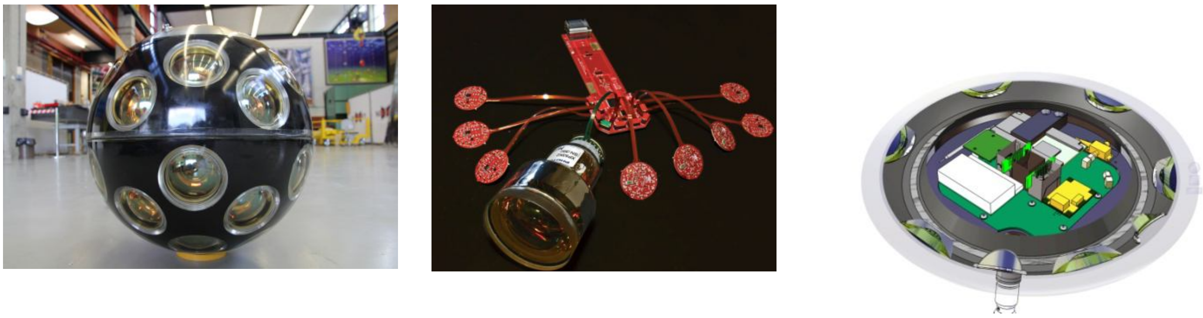

Figure 10 Prototype of a multi-PMT DOM (left); the Octopus signal collection board with a Photonis PMT and PMT-bases connected (middle); technical drawing of the central logic board mounted in the cooling shield (right).

Validation of the multi-PMT DOM

The concept of the multi-PMT digital optical module has been validated with several reference models of the module. The performance of the cooling system, the resistance against high pressure, the optical coupling between the photomultipliers and the glass sphere and the background rates of the glass of the sphere and the glass of the photomultipliers have been measured. A long term test with 16 photomultipliers in a hemisphere in a dark box with water has shown the feasibility of the concept. During the validation tests, photomultipliers of the Photonis company have been used. With the demise of Photonis for photomultiplier production, discussions with four other providers of photomultipliers started in 2009. This has resulted in the recent delivery of the first batches of phototubes by Hamamatsu (R6233MOD) and ETEL (D783KFLA) for use in the prototype DOMs to be deployed in 2012. The delivered photomultiplier tubes comply with the specifications presented in the technical design report. The results of the acceptance tests of these tubes have been presented during the VLVnT11 workshop [**15**]. Together, ETEL and Hamamatsu will deliver in total 150 photomultipliers for installation in the KM3NeT tower-prototypes to be deployed in 2012. Two 'mini-DOMs' with each five photomultipliers are in preparation for installation in the instrumentation line of ANTARES. These mini-DOMs will be read out using an interface to the ANTARES readout system. In addition to these two mini-DOMs, one full DOM will also be installed in the ANTARES instrumentation line. This DOM will be readout using a prototype of the foreseen readout system for KM3NeT. Together, the deployment of these DOMs will allow an early long-term in-situ benchmark test of the functionality of the multi-PMT DOM and the KM3NeT readout and DAQ system. Installation of these DOMs in ANTARES is foreseen for early 2012. Experience with these DOMs will be input for another in-situ test of the multi-PMT DOMs which is foreseen also in 2012 with the deployment and connection of a small version of the KM3NeT tower at the Capo Passero site. In this tower, three DOMs will be installed again for an in-situ test of the functionality of the DOMs and for a test of the KM3NeT readout and DAQ system over a distance of 100 km.

Cost estimate for the multi-PMT DOM

Based on a production of components for a total of 12800 optical modules required for the full KM3NeT detector of 320 towers, the total investment cost of the digital optical module is estimated €9551. This number does not contain the mechanical interface to the storey of a detection unit, since this item depends on the choice for the storey in the detection unit. The breakdown of the costs is presented in Table 4 in section 4.4. It shows that the cost for the optical module is dominated by the cost of the photon sensor unit, i.e. the combination of the photomultiplier tube, the HV base and the light collection ring. The cost of this combination is currently estimated at €195. Options for reduction of this number are being studied. The cost of the HV base of the photomultiplier tubes will be reduced by further integration of functionalities in the ASIC on the base. A submit of the updated ASIC design is expected early 2012. In addition, it is being investigated whether using a material like Perspex-G for the convex front end of the tube to match the radius of the glass sphere is feasible. If feasible, this would replace the light collection ring and would reduce the cost for the photon sensor unit and ease the assembly of the DOM.

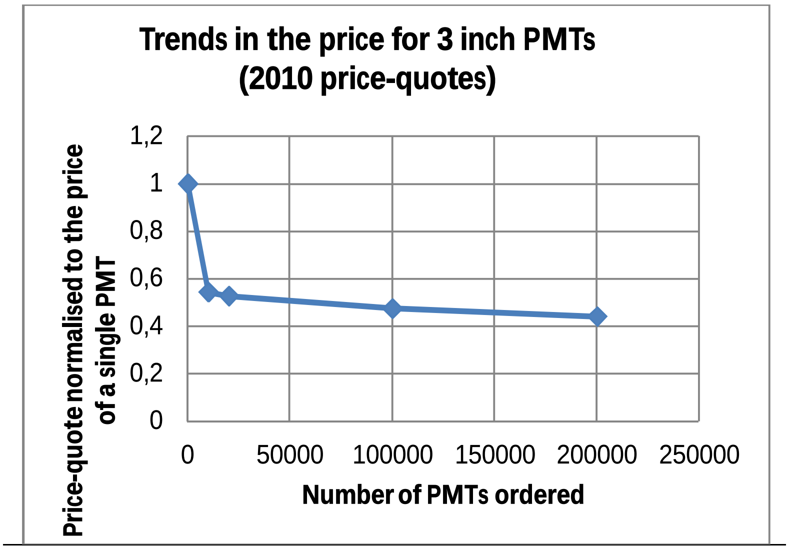

Figure 11 Trends in the price for 3-inch PMTs as function of the total amount of PMTs ordered. Calculated using 2010 price-quotes. The price is normalised to the price of a single PMT.

Besides ETEL and Hamamatsu, also the MELZ Company is preparing for delivery of their first prototype photomultiplier end of 2011. The newly established Chinese company Zhan Chuang Photonics, which has purchased the Photonis technology for photomultiplier production, has planned delivery of a first prototype in the summer of 2012. Of the two major PMT manufacturers Hamamatsu has indicated that the level of 50000 per year is not unrealistic, ETEL will for an up front investment provide a production line capable of the required numbers. They have presented cost estimates for the mass production of photomultipliers for KM3NeT, both for the full detector of 320 towers and for smaller batches. In Figure 11 the dependence is shown of the price for a 3-inch PMT on the total number ordered. For this figure the price-quotes made in 2010 are used. The final choice for photomultiplier companies for KM3NeT will be the result of a tendering procedure that is expected to start end 2012. The competition of the four companies allows for the choice for a multi-source mass production of the photomultiplier tubes for KM3NeT, which is attractive for the pricing of the photomultiplier tubes, but also is an assurance against bankruptcy of companies or against the halting of production of producing photomultiplier tubes such as experienced with the Photonis company. The cost of the custom electronics boards inside the digital optical module is estimated at €2160. This number is dominated by the cost for the central logic board with a FPGA and the e/o conversion board with the REAM (Reflective Electro-Absorption Modulator). About 2% of the total cost of the module is contributed to the instrumentation inside the optical module: an acoustic piezo element, a nanobeacon, a compass, a tilt-metre and a pressure gauge.

Risk and reliability analysis for the multi-PMT DOM

The risk analysis of the multi-PMT digital optical module is somewhat complicated as it is a custom design, but some of the components have been used extensively. For example, the glass spheres have a leakage probability below the percent level. Experience with ANTARES has shown that leakage occurs primarily on submersion and does not increase significantly with time. For KM3NeT this is acceptable only if this error does not propagate in the tower. Each optical module is therefore galvanicaly separated from the rest of the system, avoiding the propagation of any leaks by corrosion. Photomultiplier tubes are typically very reliable items. Typical FIT rates (failures in 10^9 hours) are around 10. The photomultipliers run at a gain of 10^6 and their individual photocathode area is small, therefore the integrated anode charge is small. Degradation of the performance of the photomultiplier during the foreseen lifetime of 15 year of the telescope will therefore be in the order of 1-2%. The optical modules contain many photomultiplier tubes so a single failure only causes a slight reduction in efficiency rather than a complete blind spot. The FPGAs have typical FIT rates in the range of 10 to 50 depending on their size and configuration. FIT rates of the custom electronics have been estimated from component reliability figures. The overall failure rate of the optical module has been estimated at less than 500, equivalent of 0.5% in 10 years operation. The failure is then defined as at least one photomultiplier tube becoming inoperative.

Assembly of multi-PMT DOMs

In compliance with a detector of 320 towers with 40 DOMs each or 640 springs with 20 DOMs each, a total of 12800 digital optical modules will have to be assembled for deployment within a period of four years. Although most components of the optical module can and will be mass produced in industry, assembly of the optical module in industry is not foreseen. Instead, the production model is to establish within the consortium dedicated DOM-assembly sites with dedicated and trained personnel hired on project basis. As a first step in the design of DOM-assembly lines the assembly procedure of the optical modules of ANTARES has been studied. This resulted in a preliminary detailed description of the foreseen assembly procedure as presented in the technical design report. The procedure has been further analysed during the preparatory phase, based on the experience with the assembly of several prototype optical modules and experience with mass production of components for the LHC detectors at the research labs in the consortium. It resulted in the recommendation for 6 separate DOM-assembly sites each with 200 m^2 space for two parallel assembly lines and 200 m^2 for storage of components and optical modules. Per assembly site, 8 fte will be required during four years, a total of 192 fte-year. The assembly and quality control procedures will be further optimised during the assembly of the prototype DOMs for the deployments in 2012. In parallel, the first prototype assembly line for mass production is being designed and will be installed in 2012 at one (possibly more) of the research labs in the consortium. The choice for six separate DOM-assembly sites has been made deliberately to allow for the various groups and institutes to locally involve personnel and make the presence of KM3NeT very visible. If this turns out not to be required, less assembly sites with more parallel assembly lines is equally feasible. This would reduce the overhead cost, e.g. in the case of a single production site it is estimated that a total of 174 fte-year would be required.

4.3 Single-PMT Optical Module

Also the design of a single-PMT optical module has been described in detail in the technical design report. Moreover, in all precursor neutrino telescope detectors, the use of a single large photomultiplier tube was the common feature. Typically, the deep-sea telescopes utilize glass containers with a diameter of 17 inch and the Antarctic telescopes those with a diameter of 13 inch. The diameter of the photomultipliers used is 15 inch for the DUMAND, BAIKAL and NESTOR experiments, 10 inch for the ANTARES and IceCube telescopes and 8 inch for the Amanda telescope and DeepCore. In IceCube a storey can consist of a single optical module, whereas in the deep sea multiple single-PMT optical modules per storey are required to allow for the reduction by local coincidences of background hits from ^{40}K decay and bioluminescence in the seawater. In IceCube the electronics is contained in the same glass sphere as the photomultiplier, a natural choice for use in the Antarctic ice. The deep-sea of ANTARES allowed for the choice of a separate electronics container on each storey. During the KM3NeT Design Study, the use of both 8 inch and a 10 inch photomultiplier tubes has been studied in a storey-configuration of 6 optical modules and one electronics container per storey. The diameter of the glass sphere of the optical module was chosen to be 13 inch. A nanobeacon for timing calibration is included in two of the six optical modules on a storey. With three different Hamamatsu photomultipliers the influence of the Earth's magnetic field on the performance of the tubes has been measured. These three tubes were a 10-inch R7081 tube with a standard bialkali photocathode and two 8-inch R5912 tubes, one with a standard bialkali photocathode and the other with a super-bialkali photocathode. These validation tests showed that a mu-metal shield against the influence of the Earth's magnetic field is required. Other tests showed that the increased quantum efficiency of the 8-inch super-bialkali tube almost compensates its smaller detection surface compared to the 10-inch tube [16]. In ANTARES, it has been observed that there is a presence at the level of a few percent of after-pulses that have large pulse-heights. This is due to ion-acceleration to the photocathode. The rate of these large pulses scales according to the singles rate. With a typical background rate of 50 kHz in the deep-sea this translates to a rate of L1-hits (see section 0) between 250 and 500 Hz. To remove this background a significant cut must be placed on the number of L1-hits required for recognising neutrino events which – for large detectors such as KM3NeT – reduces the sensitivity of the detector significantly.

Cost estimate for the single-PMT OM

The total investment cost of a single-PMT optical module has been estimated €2644. This number includes the cost for the HV base and the connection to the electronics container but does not include – as opposed to the multi-PMT optical module – the cost of the readout electronics. The breakdown of the cost is presented in Table 4 in section 4.4. The cost of the PMT-unit, i.e. the photomultiplier tube, the base and the mu-metal shielding system is estimated at €1380. In Figure 12 the dependence is shown of the price for a large photomultipliers on the total number ordered. For this figure the price-quotes made in 2010 are used. The trend is shown for a standard 10-inch PMTs and a HQE 8-inch PMTs. In contrast to the multi-PMT optical module, the readout and data acquisition electronics for the single-PMT optical module is stored in a separate electronics container. This container is shared by six optical modules and requires six storey cables with copper wires for connection between the electronics and the optical modules. The total cost of the container including the electronics is estimated €5500. The breakdown of the total cost for a storey with six single-PMT optical modules is presented in Table 4 in section 4.4. The cost for the mechanical interface between the optical modules and the mechanics of the storey and that of the electronics container and the storey is not included in the table. On a tower-storey of six optical modules, two of them contain a nanobeacon. Together with an external hydrophone and a compass/tiltmeter in the electronics container about 5% of the total cost is attributed to instrumentation.

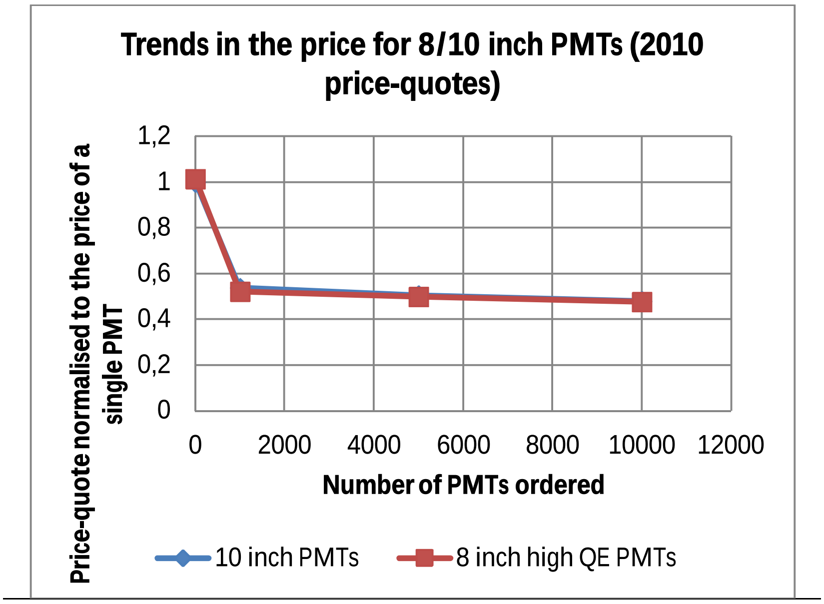

Figure 12 Trend in the price for 10-inch and HQE 8-inch PMT as function of the total amount of PMTs ordered. Calculated using 2010 price-quotes. The price is normalised to the price of a single PMT.

Risk and reliability analysis of the single-PMT OM

The risk analysis of the single-PMT optical module and the electronics container can be based on the experience with the ANTARES neutrino telescope. About 900 optical modules have been deployed since 2006. Since then about 3% of the optical modules (27 out of 900) have leaked, of which about 50% due to a vacuum valve with O-ring that is no longer produced by the supplier. About 1% of the electronics containers (2 out of 300) have leaked. For KM3NeT, with regard to leakage, the same conclusions apply as formulated for the multi-PMT optical module. Also in this case, the propagation of water leaks from the electronics container to the backbone is prohibited by a galvanic separation. The FIT rate for the large photomultiplier tubes is not significantly different from those for small photomultipliers. A failure of an electronics container will eliminate all optical modules on the corresponding storey.

Assembly of single-PMT OMs

The assembly of the single-PMT optical module is well known from the ANTARES detector, for which the first 100 optical modules were assembled in industry and in a time spam of 17 month a total of 800 optical modules were assembled within the collaboration. For a telescope of 320 towers a total of 38400 optical modules must be assembled in a period of four year. For this, assuming a single assembly site, a total of 151 fte has been estimated, i.e. during four year of construction, about 37 fte is required for the assembly of the optical modules. In contrast to the multi-PMT optical module, assembly of the single-PMT optical module in industry is considered feasible, although an attempt to to this failed. Also for the electronics container, the experience with the assembly of the ANTARES electronics container is invaluable. In total 50 fte year is estimated for the assembly of the 6400 electronics containers in the full KM3NeT detector. I.e. during four years of construction, about 13 fte is required for the assembly of the electronics containers. Assembly in industry of the electronics container is not considered.

4.4 Comparison between multi-PMT and single-PMT optical modules

The design of the multi-PMT digital optical module is the result of a careful analysis of the optical modules in other neutrino telescopes, in particular the ANTARES deep-sea detector. From this analysis it became clear that – besides the need for a seriously cheaper solution – two major challenges should lead the design concept: the high background and the high pressure environment of the deep-sea.

The first challenge of the high background has led to the choice for a segmentation of the photocathode area. This segmentation will aid distinguishing single photon hits from two-photon hits, which is important for the reduction of random background hits from ^{40}K decay and bioluminescence in the seawater. Section 0 contains the details of the readout and trigger implementation. For each hit photomultiplier the time over threshold (ToT) will be measured. This provides, for large pulses, a logarithmic dependence of the ToT on the pulse height. At small intensity, the ToT is less accurate, but the hit pattern will distinguish between 1, 2 or more photons. Two-hit separation is at the single photon pulse width for a typical threshold of 0.3 spe. Effectively, multiple photons in the optical module are distinguished by counting photomultiplier hits rather than determining pulse-height. Since photomultiplier tubes in the module also are pointing upwards up to about 45 degrees above the horizon, the background from atmospheric events will be well measured thus allowing for a better understanding of this background and as a result to a better reduction. Essential in this is the concept of all-data-to-shore for the data acquisition, which will allow for elaborated trigger studies.

The second challenge of the high ambient pressure in the deep sea has led to a design with the photocathode area and the instrumentation of a full ANTARES storey in a single glass sphere together with the electronics. With only one high pressure transition through the glass and a galvanic separation from other modules, the risk of a water leak per photocathode area in the detector has been considerably reduced compared to the design of ANTARES with 6-9 high pressure transitions per storey and without galvanic separation of the optical modules and the electronics container.

As already stated in the introduction, in January 2011 the SPB of the KM3NeT Preparatory Phase project decided to give priority to the validation of the multi-PMT digital optical module (DOM), in particular in a tower structure with a multi-PMT optical module at either end of a 6 m long storeys. The physics performance of such a structure is addressed in chapter 0. Here we will address the validation of the multi-PMT digital optical module, its reliability, the feasibility of mass production of the modules, both in terms of investment cost and fte required for assembly and the possibility of industrial outsourcing. We will address these issues in comparison of a two multi-PMT DOM storey with a storey containing six single-PMT optical modules and an external electronics container.

In sections 4.2 and 4.3 the validation and reliability analysis of the optical modules has been described. Clearly, validation of a single-PMT optical module is delivered by the ANTARES detector. Although the lessons learned from the performance of these modules and the electronics containers have been taken into account in the design of the multi-PMT digital optical module and tests have shown the validity of the multi-PMT module in the lab, the in-situ validation of the module is still pending. The installation of two mini-DOMs and a full DOM in ANTARES and the deployment and connection of a prototype tower with several multi-PMT DOMs installed will be the final steps in the validation procedure. Since the multi-PMT optical modules contain many photomultiplier tubes a single failure only causes a slight reduction in efficiency rather that a complete blind spot as in the case of a single-PMT optical module. In Table 5 the design and production features of the multi-PMT optical module and the single-PMT optical module required in a full KM3NeT detector are summarized. Since the multi-PMT digital optical modules also contain calibration instrumentation and all electronics boards, also the cost and assembly effort for the electronics container and the external instrumentation is presented to allow for a proper comparison of the same functionality per tower-storey.

	Multi-PMT DOM	Single-PMT OM	Electronics Container	External instrumentation
Item	**Cost [€]**	**Cost [€]**	**Cost [€]**	**Cost [€]**
Glass sphere	400	350		
Titanium vessel			2000	
Electronics	2160		2300	
Mechanics	120	60	30	
Cooling	115		70	
Instrumentation[1]	411	54		1051
Penetrator	300	150	1100	
PMTs+bases+light collection rings	6045			
PMT+base+mu-metal shielding		1380		
Connection to electronics container		650		
Total	*9551*	*2644*	*5500*	*1051*
Nr. of items required per storey in a tower	2	6	1	1
Total cost per tower-storey	**19102**	**22415**		

Table 4 Cost breakdown for the two multi-PMT digital optical module (DOM) on a storey of a DOM-tower and of six multi-PMT optical modules, the external electronics container and the connection between them and the external instrumentation on a storey in a single-PMT OM tower. The total cost per storey is for the same functionality in both tower configurations. The cost for the mechanical interface between the modules and the mechanics of the storey is not included in this table.

	Amount	Investment [M€]		Assembly [fte year]	
Multi-PMT DOM including electronics	12800	123		192	
Single-PMT OM including connection to the external electronics	38400	102	144	151	201
Electronics Container and an external hydrophones	6400	42		50	

Table 5 Estimated total investment cost and assembly effort in fte-year for the optical modules in a full KM3NeT detector. In the case of utilization of single-PMT optical modules, the cost of the electronics container and external hydrophones need to be taken into account as well for comparison of the same functionalities. In all cases the mechanical interface with the storey mechanics is not included. For comparison, the fte-estimates are for a situation with a single assembly site for the optical modules in both cases.

Comparison of the numbers shows that the total investment cost for the multi-PMT DOMs in a KM3NeT detector is lower than that for the single-PMT OMs with the external electronics containers. The numbers for the total assembly effort are similar for both configurations. Clearly, the number of items to be produced for a KM3NeT detector with multi-PMT DOMs is much less than in

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[1] Each multi-PMT DOM contains an acoustic piezo element, a compass, a tilt meter and a nanobeacon. On a storey of 6 single-PMT optical modules, only 2 OMs contain a nanobeacon. An external hydrophone is connected to the electronics container, which also houses a compass and a tiltmeter.

the case of a detector with single-PMT optical modules. The complexity of the electronics between the two solutions will be similar; packaging of both the photomultiplier tubes and the electronics in the same vessel as in the multi-PMT DOM will be more complicated. On the other hand, testing of the plug-and-play multi-PMT DOM and its integration in the detection unit will be easier than in the case of the single-PMT optical module. The cost estimates of components are based on, in descending priority, industrial quotations, corresponding costs as occurred in the pilot projects, public catalogues, and informal or confidential statements of providers. The costs of the photomultipliers are estimated according to informal and confidential statements of the four corresponding companies. Most components will be produced in industry. For those components that have to be produced in very large quantities, such as the photomultipliers, multi-source production will be sought to reduce the risk of serious delay of the KM3NeT building project by demise or malfunctioning of companies.

Outsourcing in industry of the assembly of the multi-PMT optical module with the electronics inside is not foreseen. Instead, the production model is to establish dedicated assembly lines within the consortium with dedicated and trained personnel hired on project basis and supervised by the staff of the institutes. This production model has been successfully applied many times for the mass production of e.g. detectors for the LHC experiments. Experience has shown that for detectors which require a high level of quality control, the model allows for a cost-effective high-quality production. Assembly of the single-PMT optical module in industry is considered feasible, based on the experience with the first about hundred of the ANTARES single-PMT optical modules which were manufactured in industry. As for the multi-PMT optical module, assembly of the electronics container by industrial companies has not been foreseen.

4.5 Towers

During the last two years, two different tower-configurations have been considered. One is utilising single-PMT optical modules, the other one multi-PMT optical modules. Both towers consist of 20 bar shaped, 6 m long storeys with optical modules. The towers are connected to the seabed infrastructure with a wet-mateable connector.

The tower-configuration with single-PMT optical modules is described in the technical design report and has been further worked out during the preparatory phase. Details can be found in a report for the European Committee as a deliverable of one of the work packages [**17**]. A storey in this tower contains six optical modules each connected via copper wires with an electronics container on the same storey. An electro-optical cable runs the full length of the tower connecting the electronics containers on each storey. Each storey will have a unique optical link with the data acquisition on shore. The optical modules and the electronics containers are galvanicaly isolated to prevent water leaks to propagate in the tower. The development of this tower configuration has been abandoned after the decision of the consortium in January 2011 to give priority to the validation of the digital optical module (DOM) and a tower configuration with storeys with a DOM at either end. In this tower configuration, christened DOM-tower, the multi-PMT digital optical modules are attached to breakouts in flexible electro-optical backbone cables running the full length of the tower at both sides. As opposed to the single-PMT tower, in this tower each optical module has a unique optical link with the data acquisition on shore. Each optical module is galvanicaly isolated.

The choice for fibres in the backbone of the tower as opposed to copper wires is driven by several key performance indicators: (1) timing calibration; (2) signal attenuation; (3) bandwidth; (4) cost. In two independent studies during the design study the feasibility of the use of copper wires in the backbone of the tower has been investigated. In one project, the use of VDSL2 communication over twisted pair has been studied; in the other project the use of coax cable. From these studies it became clear that transitions between the copper and fibre domain complicate timing calibration and that it is preferable to remain in the optical domain as much as possible. Signal attenuation over copper wire is more serious than over fibre; in the case of copper wires additional amplifiers in the detection unit will be required and consequently more electrical power for the unit will be unavoidable. In addition, to accommodate sufficient bandwidth in the detection unit modulation techniques must be applied which enhances the amount of electronics in the deep sea. The choice for several twisted pair copper wires would increase the diameter of the cable thus introducing a larger drag and would make the cable less flexible. Finally, the cost per metre of copper wires is higher than that for fibres, making the copper solution for the backbone cable not significantly cheaper than the fibre solution.

Since the consortium has decided for the validation of the DOM-tower [**17**], which is not described in the technical design report, we will summarize this configuration here. A drawing of the storey is presented in Figure 13. The material used for the mechanical structure is Aluminium 5083. A system of four Dyneema ropes with a diameter of 4 mm connects the storeys in such a way that each storey in a tower is positioned perpendicular to the previous one. Flexible electro-optical backbone cables are spiralled around a rope at either side of the tower. These cables are of the type Pressure Balanced Oil-Filled (PBOF) and utilize a low density polyethylene (LDPE) tube with an outer diameter of 6 mm as a conduit for the electric wires and fibre optic lines. This option for cabling provides for a reliable and configurable cable system suitable for many subsea applications. For each optical module the cable contains a separate fibre, two copper conductors run the full length. At each storey a breakout cable with 1 fibre and 2 copper conductors connects the backbone cable with the optical module. The tower is anchored to the seabed using a dead weight of 1908 kg in sea. A separate optical fan-out module – (de)multiplexing module - with DWDM (Dense Wavelength Division Multiplexing) technology is positioned about halfway the length of the cable thus allowing for a maximum of 11 fibres in the cable. A few meter above the deadweight the base structure – the lowest storey in the tower without optical modules – is positioned in such a way that a proper equilibrium position is assured. At the base structure, in a Titanium container the two flexible cables are connected to an interlink cable which at the other end connects to the seabed cable infrastructure with a wet-mateable connector. The two spacer storeys in the lower part of the structure are not equipped with optical modules. At the top of the structure a buoy system made of syntactic foam is installed to provide the 7000 N buoyancy required to keep the structure vertical. Buoyant material (a total of 2500 N) provides local buoyancy to each storey. The total drag causing a displacement of the top buoy of 144 m at a horizontal sea current of 0.3 m/s is sufficiently small in a detector configuration with a horizontal tower-distance of 180 m. A current of 0.3 m/s is considered a catastrophic event for which a deep-sea structure must be resistant.

The full tower structure of 20 storeys with connecting cables and ropes, 2 spacer storeys and the base storey, deadweight, and two top buoys is stored as a compact package. The storeys and spacers are stored in five columns (see Figure 13). The package (about 2.5m x. 2.5m x 6 m) fits in a 20 foot ISO high cube container (6.1 x 2.9 x 2.44 m) to adapt transport directives. The compact package is deployed to the seabed. Once the deployment cable is removed the structure is released with the help of a ROV and the tower can unfurl to its full length of about 900 m.

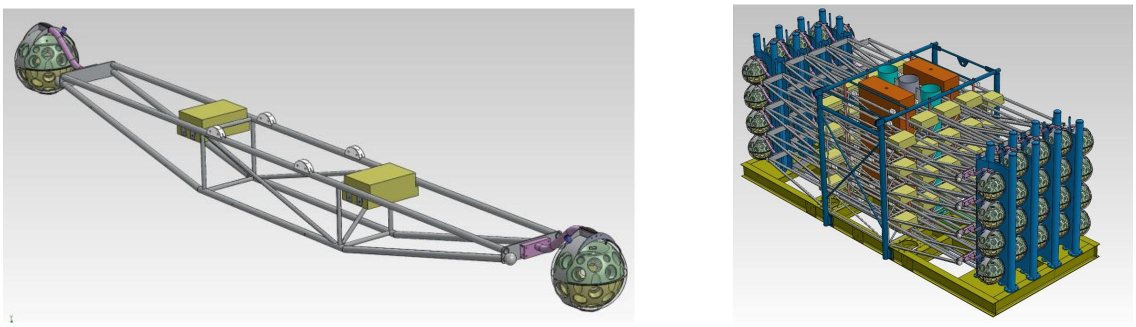


Figure 13 Left: drawing of a single storey with local buoyancy (yellow); rope and cable management is not visible. Right: stacked tower with top buoys, anchor and top buoy (orange blocks in the middle.

Validation of towers

Validation of the tower configuration with six single-PMT optical modules at each storey is no longer considered by the consortium. During 2010 one in-situ test has been performed, which showed the complexity of unfurling such a tower. A mechanical prototype of the NEMO tower which has a mechanical structure similar to the DOM-tower has been deployed successfully in February 2010 (see Figure 14). Prototypes for the DOM-tower configuration are being prepared for deployment in 2012. During these deployments, the mechanical structure of the DOM-tower, the flexible backbone cable and the deployment method will be validated. Deployment and connection to shore of a small sized tower with three optical modules is also foreseen in 2012. Validation of the backbone cable in the lab is ongoing. Although not used in neutrino telescopes so far, the technology of PBOF cables is widely utilized.

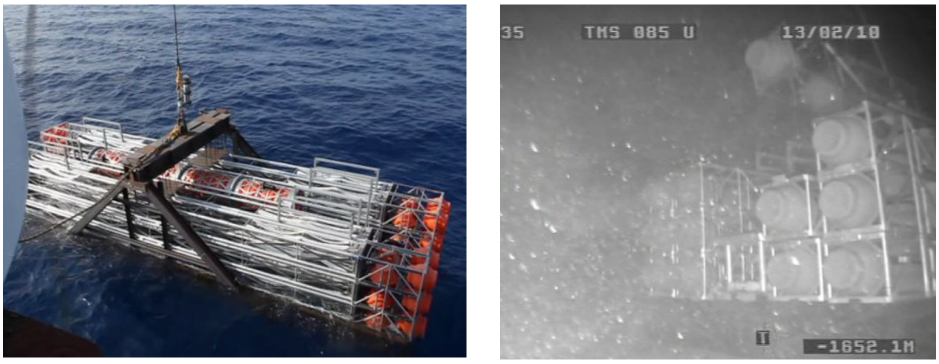


Figure 14 Deployment of a mechanical prototype of a NEMO tower with single-PMT optical modules at either end of the storeys (left). Unfurling of the NEMO tower from the seabed (right)

Cost estimate for towers

The total investment cost of the infrastructure of a tower a DOM-tower is €89800 and that for a tower with single-PMT optical modules is €55900. The breakdown of these numbers is presented in Table 6. The large difference in cost for the buoy is partly due to the fact that in the single-PMT PM tower inherently has more buoyancy delivered by the 120 optical modules and only needs six glass spheres as a top buoy. On the other hand, drag calculations for this structure has not been scrutinized to the full extent, since the consortium decided to abandon this design. The choice for two backbone cables in the DOM-tower and, as a consequence, two optical fan-out modules to allow for redundancy is another reason for the large difference in cost for the tower infrastructure. The cables run the full length of the tower, each on one side of the storeys thus providing redundancy in the tower. If the cost of the optical modules, the readout electronics and instrumentation is included, the total investment cost for the DOM-tower is €473840 and for the single-PMT OM tower €516180. The fact that the total investment cost for a DOM-tower is lower than that for the single-PMT OM tower is largely due to the fact for the DOM-tower the cost for optical modules, electronics and instrumentation is much smaller (see also section 4.4); this more than compensates the cost for redundancy of the two backbone cables and the higher cost for the buoy system.

	multi-PMT DOM-tower	Single-PMT OM tower
Tower mechanics	23300	28200
Buoy	16600	2700
Optical fan-out modules	10000	5000
Backbone cable	40000	20000
Total tower infrastructure	*89800*	*55900*
Optical modules, electronics, instrumentation plus mechanical interface to tower infrastructure	384040	460280
Total tower	**473840**	**516180**

Table 6 Breakdown of estimated investment cost for a detection unit in two different tower configurations.

Risk and reliability analysis of towers

The risk analysis of the optical modules has been presented in sections 4.2 and 4.3. Since the modules (and in case of the single-PMT OM tower the electronics containers) are galvanicly isolated water leaks in an optical module will not propagate in the tower. The risk analysis of the vertical backbone cable is somewhat complicated, as this is a custom designed cable. Many subsea electrical and optical cable and connection systems now utilize Pressure Balanced Oil Filled (PBOF) cabling solutions. Industry claims that PBOF cable systems are both sturdy and longwearing thus providing for a reliable cable system with a life expectancy of 25-30 year in the deep sea. The application of this technology in a vertical and long cable (beyond 500 m) is new. The manufacture of ANTARES interlink cables has recently changed standard dry cable to PBOF cable. This cable has been installed in ANTARES. It is an excellent opportunity to monitor its behaviour in the coming years. In case the development of the PBOF cable for KM3NeT fails, the alternative is to utilize the conventional dry cable as e.g. used in the NEMO project. In the DOM-tower two backbone cables are implemented, thus providing redundancy. At the cost of loss of redundancy, these two cables could be combined into one to reduce investment cost. It is however preferred by the consortium to let redundancy prevail over cost reduction. The unfurling method and the stability of the mechanical structure of the DOM-tower are still to be validated, although earlier deployments of prototypes of the NEMO tower have been successful. In-situ validation of the single-PMT OM tower is no longer considered.

Integration of towers

Assembly of optical modules has already described in sections 4.2 and 4.3. The integration of the DOM-tower will be similar to the procedure for a tower with single-PMT OMs described in the technical design report. Experience with the integration of similar towers for the NEMO project has been invaluable. Since the digital optical modules are designed as standalone modules the integration of the tower can be modularized. I.e. the optical modules can be assembled and tested separately; optical modules can be calibrated separately in small light-tight boxes; construction and testing of the electro-optical backbone cable in the tower can be possibly outsourced; integration of the tower is then limited to testing the electro-optical contact with an optical module. It is not necessary to test storeys with optical modules as a whole in a dark room as in the case of the single-PMT OM tower described in the TDR. Although it is not a strict requirement, it is preferred for towers to install the integration site in or close to the harbour for the deployment vessels. To comply with a production of 320 towers in a period of 4 years, it is estimated that the integration site for towers must have a hall of 300 m^2 for 3 integration lines and 750 m^2 space. The integration effort for the towers is presented in section 4.8 in comparison with that for strings.

4.6 Strings

As described in the technical design report, the multi-PMT optical module can also be installed in a string-like mechanical structure. In that design, the optical modules are suspended by two Dyneema ropes with a diameter of 4 mm, which run parallel over the full length of the string. As in the case of the DOM-tower, a flexible backbone cable with breakouts at each optical module runs the full length of the string. Additional empty glass spheres provide buoyancy at the top buoy. The anchor is a concrete dead-weight with a volume of about 1 m^3 to which the vertical mechanical ropes are connected. The weight in air of such an anchor is 2400 kg and therefore the negative buoyancy in water is 13240 N. For the deployment of the string a custom recyclable spherical launching vehicle has been designed with a diameter of about 2.1 m (Figure 15). Three sets of cable trays run from pole to pole and are offset by 60 degrees. Between the cable trays of each set, holes in the sphere provide the space for suspending the optical modules. The vehicle is loaded top down during integration of the string. First the glass spheres of the buoy are loaded on guiding rails through the hole at the North Pole. The spherical vehicle is rotated around a winding axis perpendicular to the first cable tray. The optical modules are placed in holes and kept in place by a lever blocked by the ropes. The ropes and the backbone cable are laid in the trays. The vehicle has three tubes running through them from a spreader structure at the top to the anchor. The spreader structure is secured to the anchor with an acoustic release mechanism. When released the spreader structure floats independently to the sea surface, while the spherical launching vehicle also rise to the surface unwinding the string to its full length. The launching vehicle and the spreader structure are recovered for re-use. The total weight of the loaded launching vehicle and the anchor is about 1200 kg in air. The drag of the top of the structure is calculated 95m a sea current of 0.3 m/s, sufficiently small for a detector with an inter-string distance of 130m.

Figure 15 Launching vehicle in rotator (left). Loading the launching vehicle with optical modules on a string structure in the lab (right).

Validation of strings

The mechanical structure and deployment method of the string using a recyclable launching vehicle has been validated with three separate deployments during two sea campaigns. During the last campaign in Jan-Feb 2011, the launching vehicle was re-loaded with mechanical optical modules on deck of the deployment vessel. The results have been reported at the VLVnT11 workshop [**18**]. Improvements should include the mechanical interface between the optical module and the suspension ropes and that between the optical module and the breakout box in the backbone cable. The inclusion of a real backbone cable is still to be validated.

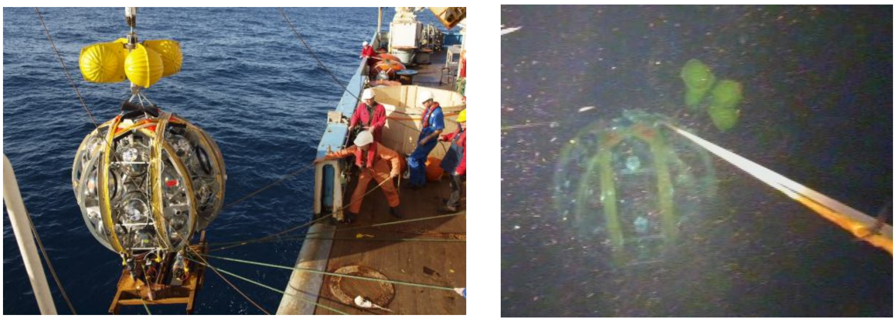


Figure 16 Deployment of a prototype of the launching vehicle loaded with mechanical prototype optical modules (left); unwinding of the string from the seabed (right).

Cost estimate of strings

The investment cost for a DOM-string is estimated € 222125. The breakdown of this number is presented in Table 7.

multi-PMT DOM-string	
String mechanics	3925
Buoy	1200
Optical fan-out modules	5000
Backbone cable	20000
Total tower infrastructure	*30125*
Optical modules	192000
Total tower	**222125**

Table 7 Breakdown of investment cost for a DOM-string.

Risk and reliability analysis for strings

All components in the DOM-string are also present in the DOM-tower. In fact, from a technical point of view the DOM-tower can be described as two DOM-strings kept at a distance of 6 m of each other by the storeys. Except for the deployment method and the stability of the DOM-string, the risk analysis is therefore similar. String-type detection units are operational in the deep sea since 2006 in ANTARES. Experience has shown that their stability is as expected. The validation deployments have shown that the concept of a spherical launching vehicle is solid.

Integration in strings

The integration of a DOM-string is described in detail in the technical design report and summarized above. Experience with string-integration during the validation tests has shown that the estimate of a total of 2-3 fte-days for integration of a string is realistic. As for the DOM-tower, tests of the strings are restricted to the test of the optical and electrical connection of the optical modules, since these modules are delivered as standalone items. Since the anchor of the string is the last component to be integrated, it is attractive to choose for the solution to connect the anchor on board of the deployment vessel. This will relax the lifting requirement for a crane in the integration site and ease transport. Since the launching vehicle is at the same time a reliable transport frame, of which a few fit together in a standard transport container, it is not strictly necessary to install the integration site near the harbour of the deployment site. It is nevertheless preferred in order to avoid very strict transportation regulations over large distances. To comply with a production of 640 strings in a period of 4 year, it is estimated that one integration site for strings must have a hall of about 300 m^2 for 6 integration lines and about 750 m^2 storage space. Also a lifting crane with a capacity of about 1200 kg is required. The total integration effort for a string is presented in section 4.8 in comparison with that for towers.

4.7 Comparison between towers and strings

The physics performance of a KM3NeT detector composed of DOM-towers or DOM-strings is presented in chapter 0. The difference in investment cost and integration cost for the three configurations is discussed in section 4.8. Here, we constrain ourselves to the results of a naive failure mode analysis, based on past experience. This naive analysis has been performed to achieve a first order estimate of the average loss of the photocathode area in a detection unit due to failures during a life time of 15 years. In these calculations, failures considered are those of photomultipliers, electronics components, components of the backbone cable and the connection of the detection unit to the seafloor network. Not considered, are failures inside the junction boxes or in the main cables to shore. The results of this naive analysis (Table 8) indicate that in first order all three configurations show an acceptable loss of photocathode area of about 10% over a period of 15 years without maintenance.

	DOM-tower	Single-PMT OM tower	DOM-string
Estimated loss of photocathode area per DU	8%	12%	8%

Table 8 Estimated first order average loss of photocathode area in a detection unit due to failure of photomultipliers, electronics, backbone cable and the connection to the seafloor network. Shown are the results of a naive failure mode analysis for the three different configurations described in the text.

Since the price of the photomultiplier has a large impact on the total cost of the KM3NeT detector, in particular in the case of the multi-PMT optical module, it has been investigated what the influence is when photomultipliers are ordered in smaller batches. For this study price-quotes for photomultipliers made in 2010 have been used. Price estimates were given for 3, 8 and 10 inch photomultipliers when ordered in various batch. For a KM3NeT detector of different sizes, the total investment cost for the detection units in the detector was calculated. For comparison, this number was divided by the total number of storeys in the detector. The result of this study is shown in Figure 17 for detector configurations with DOM-towers, towers with single-PMT OMs and with DOM-towers. The cost per storey is presented as a function of the number of detection units in the detector. The increase in cost per storey for a detector with a small number of DOM-strings reflects the higher price of the photomultipliers when ordered in small quantities. This effect is strongest for a small number of strings (<10). The cost per storey for towers with single-PMT OMs reaches a price-plateau at a detector with about 100 towers.

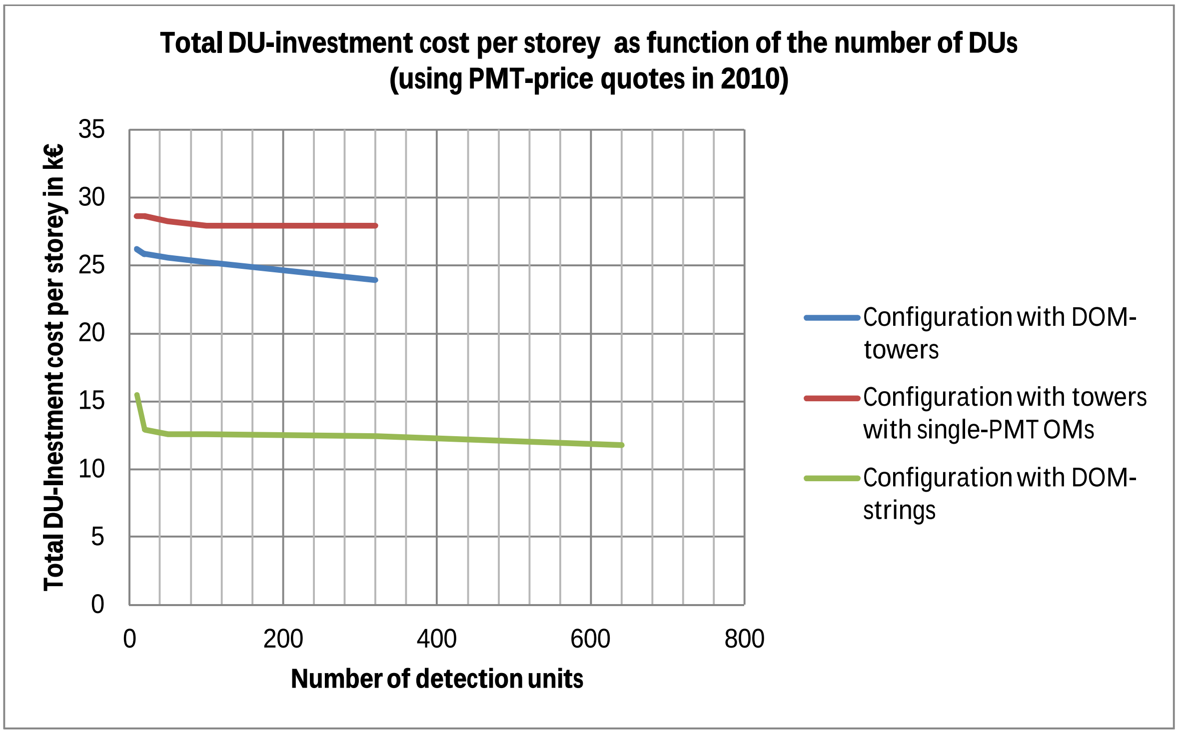


Figure 17 Total DU-investment cost per storey for three different KM3NeT configurations: DOM-towers, towers with single-PMT OMs or 640 DOM-strings. Shown is the dependence of this number on the number of detection units in the KM3NeT detector. The investment cost are calculated using price-quotes for large and small photomultipliers to be delivered in the quantities dictated by the number of detection units. Clearly, the cost per storey is lowest for a DOM-string, however this number should be multiplied by two to be compared to the cost per storey in a DOM-tower.

4.8 Investment Cost and Integration Effort

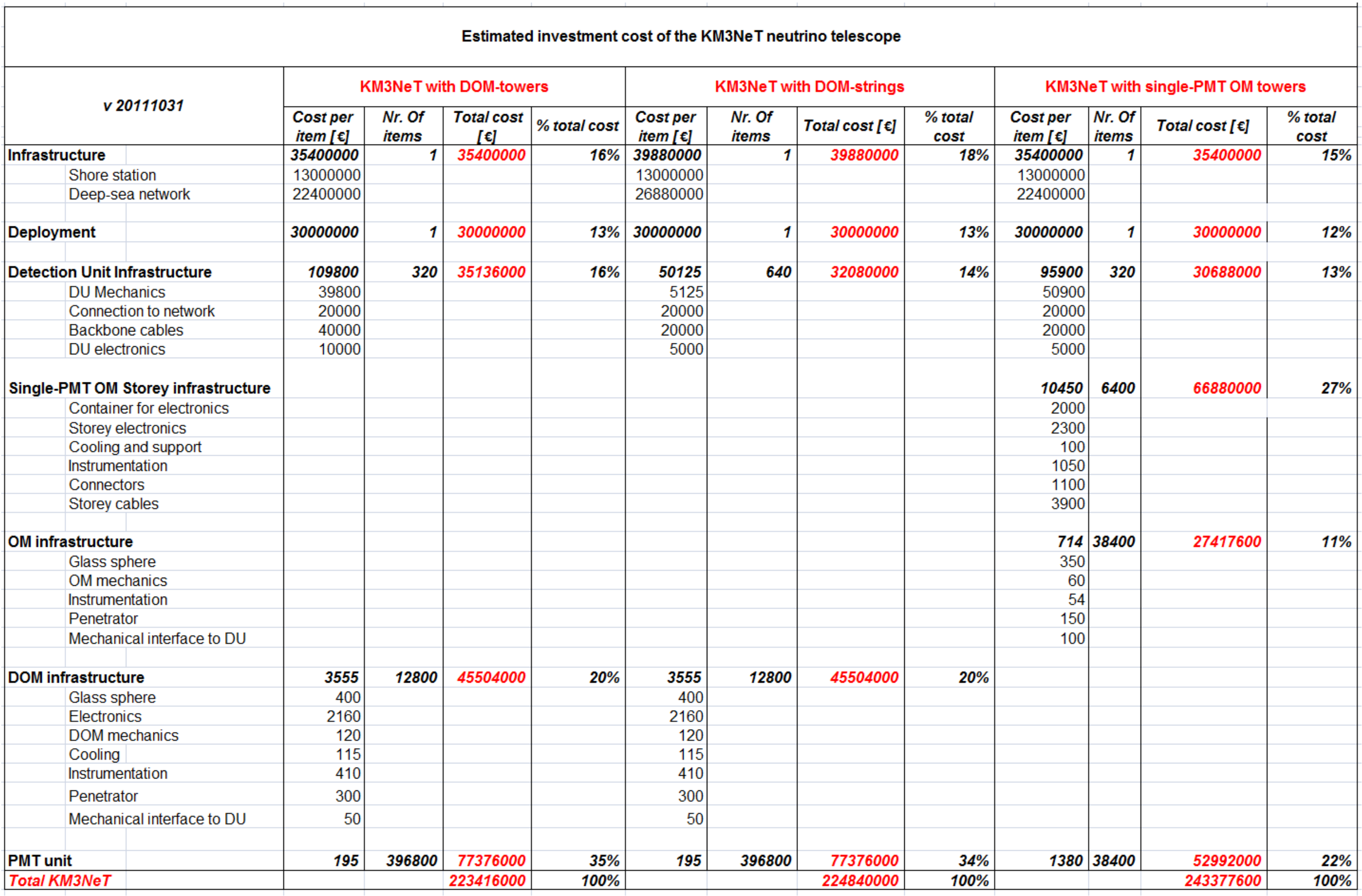
In Table 10 the estimated total investment cost for the KM3NeT neutrino telescope are summarized for the three different configurations of the detector: 320 single-PMT OM towers, 320 DOM-towers or 640 DOM-strings. Given the uncertainties, the total cost of two multi-PMT options are similar at about M€ 225. Total cost for the 320 single-PMT OM towers is M€ 240. Both figures are within the targeted range of M€ 200-250. The main cost items are listed in increasing order of the total amount required for a full KM3NeT detector. In all configurations, the PMT-unit (photomultiplier, HV base and – in the case of the multi-PMT DOM – the light collection ring or – in the case of a single-PMT OM the mu-metal shielding) is the most frequent item. Here, cost reduction will have large impact on the total investment cost for KM3NeT, in particular in the case of the DOM-tower or the DOM-string.

An option to decrease the number of relatively expensive wet-mateable connection of the detection unit to the seafloor network is to dry-connect several detection units before deployment and deploy the connected detection units as one object using two vessels instead of one. This option was considered for the DOM-string; in a preliminary contact with an off-shore company its feasibility was confirmed. The option has not been studied in detail, since the consortium has decided to give priority to the DOM-tower design. For the DOM-tower the option of multi-tower deployment is less feasible due to the larger weight and size of the towers.

The estimated assembly and integration effort for a full KM3NeT detector is summarized in**Errore. L'origine riferimento non è stata trovata.**. Given the large uncertainties, these numbers are similar for the three configurations. With a nominal value of € 100 per hour for personnel hired on project basis, the effort would add a total of 5-7 M€ to the project.

KM3NeT detector	Amount DUs	Amount (D)OMs/Electronics containers	Assembly (D)OMs/ Electronic containers [fte-year]	Integration DUs [fte-year]	Total [fte-year]
Single-PMT OM towers	320	38400/6400	151/50	72	273
DOM-towers	320	12800	192	48	240
DOM-strings	640	12800	192	24	216

Table 9 FTE required for the assembly of DOMs and the integration of detection unit for a full KM3NeT detector.



Estimated investment cost of the KM3NeT neutrino telescope

v 20111031	KM3NeT with DOM-towers				KM3NeT with DOM-strings				KM3NeT with single-PMT OM towers			
	Cost per item [€]	*Nr. Of items*	*Total cost [€]*	*% total cost*	*Cost per item [€]*	*Nr. Of items*	*Total cost [€]*	*% total cost*	*Cost per item [€]*	*Nr. Of items*	*Total cost [€]*	*% total cost*
Infrastructure	*35400000*	*1*	*35400000*	*16%*	*39880000*	*1*	*39880000*	*18%*	*35400000*	*1*	*35400000*	*15%*
Shore station	13000000				13000000				13000000			
Deep-sea network	22400000				26880000				22400000			
Deployment	*30000000*	*1*	*30000000*	*13%*	*30000000*	*1*	*30000000*	*13%*	*30000000*	*1*	*30000000*	*12%*
Detection Unit Infrastructure	*109800*	*320*	*35136000*	*16%*	*50125*	*640*	*32080000*	*14%*	*95900*	*320*	*30688000*	*13%*
DU Mechanics	39800				5125				50900			
Connection to network	20000				20000				20000			
Backbone cables	40000				20000				20000			
DU electronics	10000				5000				5000			
Single-PMT OM Storey infrastructure									*10450*	*6400*	*66880000*	*27%*
Container for electronics									2000			
Storey electronics									2300			
Cooling and support									100			
Instrumentation									1050			
Connectors									1100			
Storey cables									3900			
OM infrastructure									*714*	*38400*	*27417600*	*11%*
Glass sphere									350			
OM mechanics									60			
Instrumentation									54			
Penetrator									150			
Mechanical interface to DU									100			
DOM infrastructure	*3555*	*12800*	*45504000*	*20%*	*3555*	*12800*	*45504000*	*20%*				
Glass sphere	400				400							
Electronics	2160				2160							
DOM mechanics	120				120							
Cooling	115				115							
Instrumentation	410				410							
Penetrator	300				300							
Mechanical interface to DU	50				50							
PMT unit	*195*	*396800*	*77376000*	*35%*	*195*	*396800*	*77376000*	*34%*	*1380*	*38400*	*52992000*	*22%*
Total KM3NeT			*223416000*	*100%*			*224840000*	*100%*			*243377600*	*100%*

Table 10 Break down of estimated investment cost for a KM3NeTdetector of 320 DOM-towers or 640 DOM-string

5. Site evaluations

Site selection criteria

The criteria relevant for the choice of one or several deployment sites for the KM3NeT neutrino telescope have been discussed intensively during the Design Study phase and thereafter. The following criteria are important:

5.1 Scientific and technical criteria

Investigations of site characteristics have been intensively pursued before and during the Design Study. The site parameters impact on design, price and physics sensitivity of the neutrino telescope. The following issues are of particular importance:

- Water depth:
  On the one hand, increasing depth improves the shield against backgrounds from down-going atmospheric muons and allows for observing an increasing fraction of the sky above horizon, thus improving the physics sensitivity; on the other hand, it tightens the requirements for the pressure resistance of optical modules, electronics containers, cables etc. and also for the deployment operations and in particular the availability and costs of Remotely Operated Vehicles (ROVs).
- Distance to shore:
  Increasing distance to shore increases the price for the main cable and its deployment, as well as ship transit tiimes and thus deployment risks. It also decreases the efficiency of electrical power transmission and the optical margin of data transmission. Also, it limits the flexibility of deployment operations in case of unstable weather conditions. Short distances may allow for designs with several main cables that would be too expensive for large distances.
- Topology of the sea floor and the cable path to shore:
  A flat sea floor without obstacles like big rocks is required for safe deployment and ROV operations. The site environment should exclude deep-sea land-slides and other catastrophic events. The cable to shore must not run across sharp edges, gaps without support or very steep slopes; also, it must have a safe and smooth landing place on shore.
- Geological situation:
  The risk of major earthquakes, volcano eruptions or submarine landslides should be taken into account.
- Water transparency:
  Absorption and scattering of light in the water is the limiting factor for the distance of Detection Units (DUs) and the vertical spacing of photo-sensors on the DUs; less absorption and scattering means higher physics sensitivity, corresponding to a reduced overall capital investment. The exact dependence of the sensitivity on the optical water parameters is complex and needs further study. A precise knowledge of the water optical properties and its temporal variation is required for physics analysis; these parameters must be monitored continuously.
- Background light:
  Whereas the amount of light from decays of K40 and other radioactive nuclei is largely site-independent, bioluminescence exhibits strong geographical and temporal variations. Periods of high bioluminescence, as e.g. observed by ANTARES, reduce the overall data taking efficiency and thus the physics sensitivity. There is evidence that bioluminescence decreases below water depths of ~3000m (see TDR).

- Sedimentation and bio-fouling:
  These effects can cause a layer of reduced optical transparency on the glass surfaces of the optical modules. Even though there are indications that these layers are intermittently washed off during periods of high current velocities, they reduce the overall physics sensitivity, in particular for studies that require detecting Cherenkov light coming from the upper hemisphere. Measurements by ANTARES have shown that up to angles of 45^0 above horizon (i.e. looking upwards) there is no long-term evidence for biofouling or sedimentation effects decreasing the detector efficiency.
- Water currents:
  The KM3NeT design is safe against current velocities up to about 30cm/s; currents exceeding 45cm/s will be destructive since the anchors will start to move. Even lower current velocities could be dangerous if the current is not uniform or even turbulent. Measurements at the candidate sites indicate the 95% of the time the current velocities are below 15, 8 and 6cm/s for the Toulon, Capo Passero and Pylos sites, respectively.
- Weather and sea conditions:
  The deployment of the DUs and the deep-sea cable network will require long periods of sea operation, for which calm weather and sea conditions are required. Also, the predictability of weather changes is important to avoid operational risks.

5.2 Infrastructural and logistics criteria

Preparation, deployment and operation of the KM3Net research infrastructure will require support and infrastructure at the landfall of the selected site(s). The following issues are important:

- Availability of shore station:
  There must be a suitable site (and optionally a suitable building) to house the shore station, close to a suitable landfall location of the main cable(s) and with appropriate connection to electrical power (100 kW) and a high-bandwidth data connection to the computing centre.
- Availability of computing centre:
  There must be a suitable site (and optionally a suitable building) to house the computing centre with a high-bandwidth data connection to the European data backbones. Computing centre and shore station can be combined in the same building.
- Harbour and vessels:
  A harbour to host the deployment vessels and auxiliary ships must be close.
- Logistics requirements:
  The site installations must be easily reachable for the participants, i.e. good roads (also for shock-free transport of detector elements) and the proximity of an international airport are important. Transports of standard containers by sea freight should be possible. Appropriate accommodation must be available for project members and partners over the full year.
- Storage capacity:
  There must be storage capacity for detector components and room for on-shore pre-deployment tests.

5.3 National and local support

The host country and its scientific community should provide a series of services and guarantees:

- Operation teams:
  The core teams for the detector maintenance and servicing and for central tasks of the deployment should be provided by the host country/institute(s).

- Site manager:
  The host country/institute(s) also have to provide a manager who interfaces the project to the local authorities and population.
- Planning security:
  The host country must make a political commitment to support the project with the necessary local resources over its full expected lifetime. It must guarantee the availability of the necessary infrastructure over this period.
- Scientific community:
  A strong national science community supporting the project and representing it in the local, regional and national science, funding and science policy bodies is desirable. Measures to guarantee this local/national scientific support over the full lifetime of the project are desirable.

5.4 Site-related financial issues

It is expected that the overall funding of the project will have to be agreed upon on a multi-national, European or world-wide level. A significant fraction of the funding may be provided through European Regional Development Funds (ERDF), which very likely need to be spent locally and therefore impact on the site choice. In particular, this might imply a distributed, networked installation. The consequences of such a scenario for physics sensitivity, operation and management is currently being assessed.

However, should such a scenario become reality, it will be of utmost importance to secure the following:

- Coherent management:
  All parts of the installation must be governed by a common, site-independent body making sure that they are operated as one coherent detector. Measures have to be taken to guarantee that detector operation is fully transparent, according to operation rules and modes decided by the common governing or management bodies. The host countries have to commit themselves to this policy.

Current situation

The scientific/technical criteria have been investigated in detail during the KM3NeT Design Study. A review of the results is contained in the TDR. No show stopper was identified for any of the sites, even though it the bioluminescence situation at the Toulon site is found to be less favourable than at the other sites and may result in reduced detection efficiency. The experience from ANTARES data taking shows that this effect is equivalent to about 15-20% of data loss. Differences in the water transparency have been observed between different sites, however these measurements are snapshots in time and the amplitude of temporal variations is not well studied at all sites.

Initial simulation studies based on intermediate design configurations have been performed to assess the impact of depth and water transparency on the detector sensitivity to neutrino point sources with an E^{-2} spectrum. The results obtained exhibit a small depth dependence and indicate that the sensitivity is roughly proportional to the transmission length. However, these studies have been performed for upgoing neutrinos and fixed detector configurations not identical to the current design. The sensitivity gain of an enlarged angular acceptance above horizon at larger depth and from a geometry optimisation as a function of water transparency is under study but has not yet been quantified. The effect of atmospheric muon background and its dependence on depth is under study; we are still lacking sufficient Monte Carlo statistics to give precise answers.

The basic infrastructure and logistics criteria appear to be matched by all candidate sites; details, such as the choice of buildings etc., can only be negotiated after a basic commitment of the corresponding country. The same is true for the national and regional/local support.

Currently, some funding is secured in the Netherlands (site-independent, but dependent on a coherent site decision of the consortium), in France and in Romania. All these together currently cover roughly 10% of the overall cost. In Greece a commitment of up to 50M€ (limited to 20% of the overall cost) has been announced several years ago but the consortium was never invited in writing to a common project using these resources. Significant funding requests are pursued in France and Italy, with decisions pending and expected soon. The French, Greek and Italian funding sources are mostly of regional character (in particular ERDF) and are bound to conditions on the site and on the country/region where the money has to be spent. Explicit statements to this effect have been made by INFN and in the Greek commitment letter to the EU Commission. It seems unlikely that one of these countries will take the project lead and cover a major part (50% or above) of the overall cost. Support by and access to funding through ESFRI may be possible and could depend on the one- vs. multi-site character of the project.

In the current situation, most (but not all) partners of the consortium consider a distributed, networked installation at different sites the only pragmatic solution, provided the physics objectives are not compromised by such a scenario. Some of the Greek partners consider leaving KM3NeT in case a distributed installation is pursued.

Answers to the questions

4a. Site assessment

See TDR.

4b. Optimal detector at best site

The technical detector design as pursued to date does not generically depend on site characteristics. All technical solutions are adaptable to all sites, irrespective of the distance to shore and the water depth.

The geometry (i.e. footprint) optimisation is currently driven by the focus on Galactic sources with an energy cutoff in the 100 TeV regime, which – as compared to E^{-2} sources without cutoff – has a much more dramatic effect on the optimal detector setup than e.g. the water transparency is expected to have. The abovementioned simulation studies will result in quantitative statements on this subject.

4c. Impact of a distributed installation

For technical reasons (complexity of sea floor network, bandwidth (i.e. number of fibres) per cable to shore, ease of deployment operations, redundancy) the full KM3NeT neutrino telescope will in any case be constructed in 2, probably several independent blocks. Simulation studies indicate that the physics performance in the search for neutrino “point” sources does not suffer from such segmentation. (See chapter 3.5) A distributed but networked installation therefore does not significantly compromise the priority physics objectives, provided the individual blocks are sufficiently large (the critical size if of the order of 1 km^3 of instrumented volume, i.e. IceCube-like). No results are currently available on the impact on shower analyses, which however have lower priority (see chapter 3.4)

For the construction, the following additional costs arise as a consequence of multiple sites:

- Additional shore infrastructure (shore station, online computing, connection to high-bandwidth backbones, infrastructure for voltage supplies etc.). Since the investment cost for the online computing scales with the number of independent detector blocks, the extra costs for multiple sites are expected to be limited to the provision of housing, power and bandwidth.
  A generous estimate of the extra infrastructure cost per site is therefore 1 M€.
- Additional vessels, tools and shore infrastructure for deployment. The corresponding costs depend on the time schedule, i.e. whether the deployment operations at different sites are pursued in parallel or sequentially. The latter case is equivalent to deployment in one site as far as overall time schedule and vessels are concerned (at least to the extent that vessels can easily be moved between sites). A parallel deployment would require additional vessels and crews, however for a shorter period (i.e. the same integral time); there would be overhead in training crews and equipping vessels.
  The shore infrastructure (building to store and possibly test/calibrate detection units) is included in the item above.The overall additional cost cannot be reliably estimated but is not expected to exceed 2 M€ overall.

Note that no additional components are required due to the modular structure of the neutrino telescope. Also note that logistics will be more difficult but not more expensive since the integration of the detection units is planned to be done centrally in several labs of the consortium and the ready-to-deploy detection units are then transported to the deployment sites.

For operation, clearly additional personnel will be necessary for servicing the online computing farm and maintaining the shore infrastructure. We assume that the actual detector operation (adjustment of online filters, run control, data quality control) will be done remotely. Nevertheless, a 24/24 maintenance service at the shore site is necessary; a crew of 6 people is deemed necessary, corresponding to 1 M€ per year per extra site (including overhead).

The efforts for calibration and data analysis will not depend strongly on the number of sites since the marine environment in any case requires continuous monitoring and a calibration performed separately for each detector block at short intervals (typically minutes). Reconstruction and simulation software will be run independently for the individual blocks, whether or not they are at one or several sites. Some overhead can be expected from the enhanced effort to provide appropriate sets of environmental parameters at different sites for the simulations, but once the monitoring machinery is in place this effort is moderate.

The above-mentioned additional effort for installation at different sites results in enhanced funding resources and, in addition, in further advantages such as:

- increased redundancy in the availability of deployment resources;
- reduced dependence on local issues (phases of high bioluminescence, power outages, etc.)
- reduced impact of local catastrophic events (earthquakes, landslides, etc.);
- increased versatility of the infrastructure for earth and sea sciences

4d. Use of different sites without splitting the detector

Currently, no such scenario appears to be realistic. This could for instance be different in a situation where one of the partner countries takes a strong project lead and the remaining partner countries could use their sites for test/prototyping efforts and for earth and sea science purposes. However, as stated above, this is not the case.

6. Project risk

Evaluation of the risks for the project to build the KM3NeT facility requires the identification of threats to which a probability on a scale from 1 (low) to 5 (high) will be assigned and the impact on the project will be classified as low, medium or high.

As a first step threats have been generally categorized in technical and programmatic risks. Each of these can be caused by internal or external factors. Table 11 shows in more detail the categories that have been recognised.

Programmatic threats		**Technical threats**	
External	Politics/Strategy	External	Context
	Legal/Regulatory		Definition
	Industrial politics	Internal	Design
	Organizational		R&D activities & prototypes
	Financial		Logistics
	Media		Realisation
	Environment		Exploitation
Internal	Logical sequence		
	Project management		
	Performance management		
	Organisational/Resource		
	Budget		
	Contractual/Legal		
	Safety		
	Suppliers/Manufacturers		

Table 11 Categories of threats for the project of building the KM3NeT facility.

In each category preliminary initially conceived threats have been formulated (see the Appendix B). Further iteration inside the consortium is still to be organised to evaluate these threats and assign the probability of occurrence and the impact on the success of the project of building the KM3NeT facility. Below a preliminary inventory of the level of criticality of the major threats is given for each of the categories.

Programmatic threats

The main external programmatic threat to the project is a lack of funding or a funding profile which does not match the foreseen spending profile of KM3NeT. The total investment cost of the infrastructure was worked out in the TDR and is within the targeted range of at M€ 200-250. This estimate has been confirmed in subsequent studies. It is based on the experience with ANTARES, offers from industry and prices of standard components. As such, the cost risk is limited. However, such a sizeable amount requires contributions from regional, national and European funds. The currently secured funds are insufficient for the immediate start of construction. At the time of this writing, proposals have been submitted in France, Greece and Italy to acquire funding from the structural funds for regional development of the 7th Framework Programme of the EU as well as national funds. The lack of available funds may delay the construction of the infrastructure. A phased construction may alleviate the immediate funding but it will also postpone the scientific results. Allocation of the funds with requirements of ab unrealistic spending profile will also influence the project negatively.

Another threat to the project could be a too slow convergence to the creationof a collaboration, including management, for the construction phase of the project. This is related to the lack of immediate funding and is likely to be solved when about half of the required investment budget for construction is committed. Currently, the KM3NeT community is organised in a consortium that has been formed to execute the design study and the preparatory phase of the project. For the construction phase, the choice has been made to establish an ERIC (European Research Infrastructure Consortium) to be signed at ministerial level of the participating countries. First steps have been taken in formulating a MoU for the funding of the construction of the prototypes to be deployed in 2012. This is to assure that after the end of the preparatory phase in February 2012, these projects can be completed and the tendering procedures for mass production can be initiated at the end of it.

The site-issue has divided the groups in the consortium for a long time and has not been fully resolved yet. Nevertheless, it has been shown that a distributed neutrino telescope with building blocks of about the size of IceCube has no discernable effect on the science potential of the KM3NeT neutrino telescope. From a technological point of view a remotely operated distributed network of telescopes with the same technology and a common data centre is feasible with only small additional cost. However, within the consortium full consensus has not yet been reached. This lack of consensus is the clear and present danger to the successful construction and operation of the KM3NeT facility.

Technical threats

The design of the KM3NeT detector has been built on the experience of the pilot projects, particularly the ANTARES detector. From these projects we have recognised potential threats and have alleviated many of them, such as propagating failures and the risk of leaks. This has resulted in a design that not only is significantly cheaper, but also passes the reliability criteria of less than 10% optical modules failures in 10 years, at least on paper. However, a few potential threats remain.

One of the external technical threats to the project could be the large scale of the project. In comparison to ANTARES, the enlargement is a factor 50 and compared to IceCube it is still a factor of more than 5. Although the scaling up is considerable, it is fortunate that a neutrino telescope is a relatively simple detector because of the fact that all sensors are identical. Compared to the complexity of the LHC detectors for which many of the institutes in the consortium have built components in large numbers, the sensors of KM3NeT are relatively simple. A downside to the simplicity is that some of the items are required in very large quantities from a restricted number if vendors viz PMTs.

A complication particular to KM3NeT are the logistics of the sea operations. Building on the experience with ANTARES, it is expected for KM3NeT these operations will quickly become common place, in particular if dedicated vessels and ROVs with dedicated crews can be employed for the full period of construction.

A possible technical threat to the project is the quality of the deep-sea components. In particular, experience in ANTARES has shown that the quality of connectors and vertical cables produced in industry can be critical. However, lessons have been learned for the design of the KM3NeT telescope and the number of connectors per photocathode area has been considerably reduced in comparison to ANTARES. Another experience from ANTARES is that industry is not used to the deployment of long vertical cables and technical input from the consortium for the realisation of such cables is indispensible. Although industry provided feasibility studies that have shown that flexible oil-filled cables are a viable solution for the KM3NeT vertical cable, they seem as yet unwilling to commit to the design and production of such an item. The consortium has therefore the design and validation into its own hands. If the cable cannot be validated in time, the alternative is to use a dry cable. Such a cable has the disadvantage that it is more expensive, is less flexible and requires more complicated handling during assembly, but it has been shown to work in the prototype NEMO tower.

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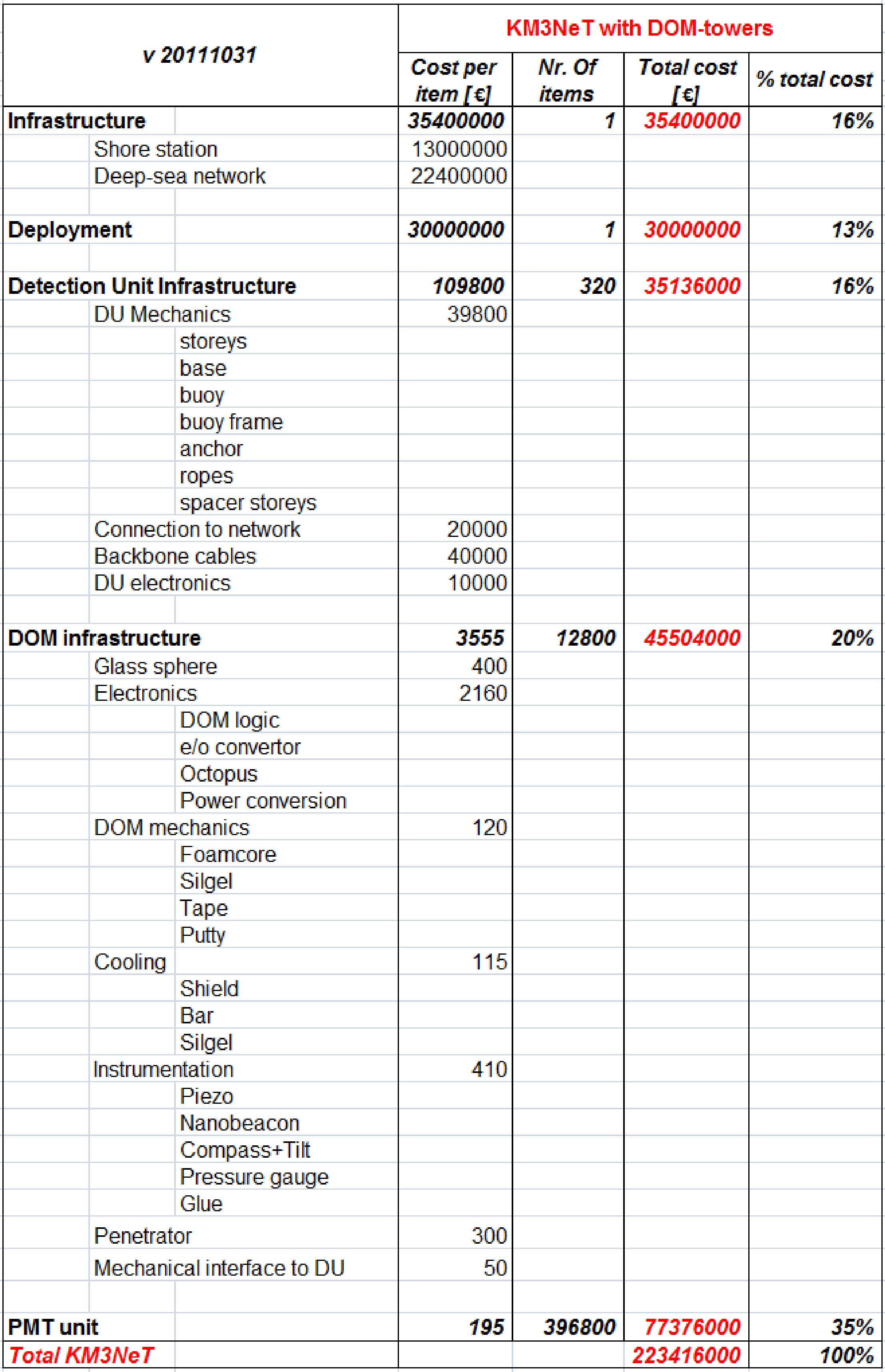
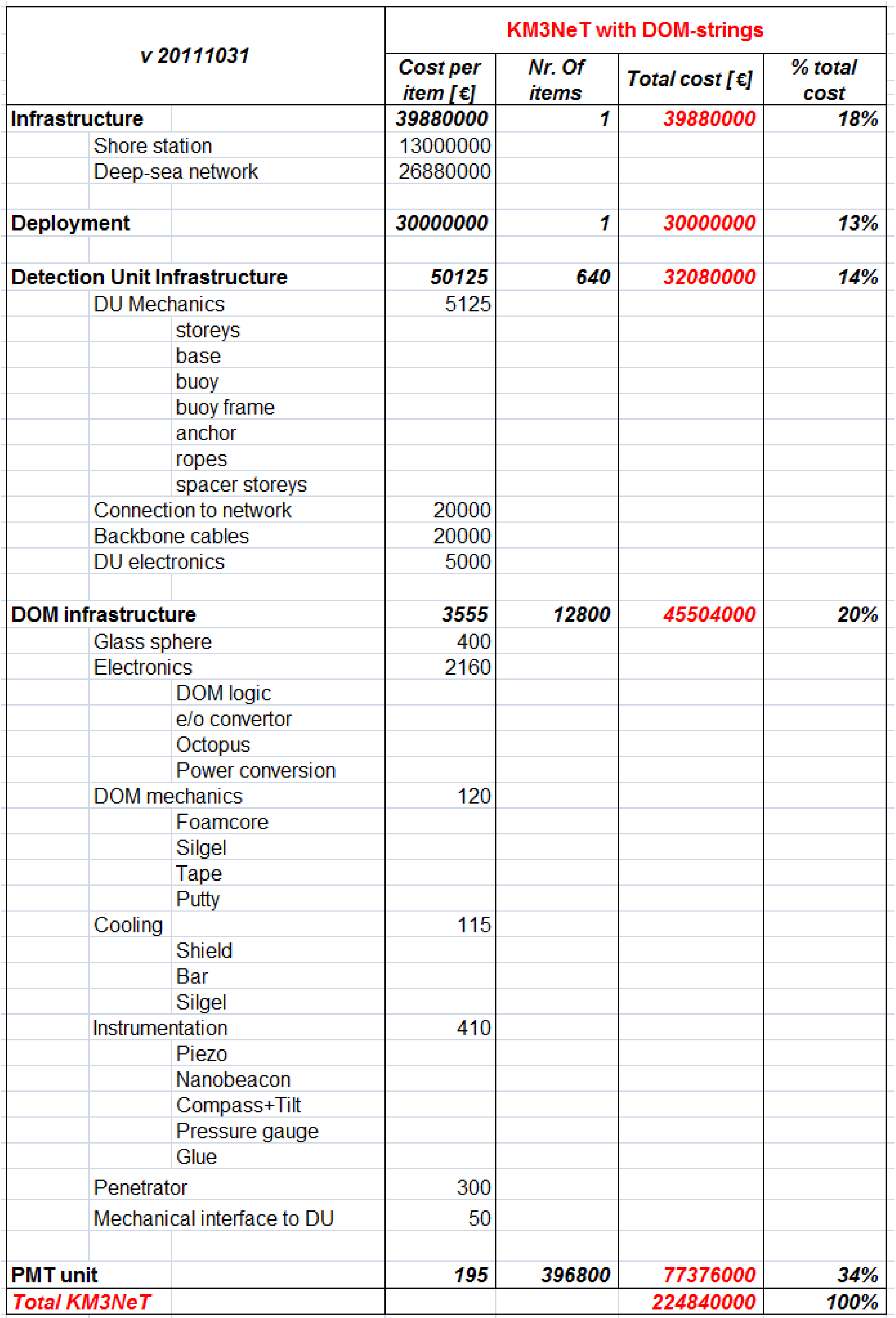
Appendix A: Estimated cost investment

In the tables below, the estimated investment cost for the three configurations of a KM3NeT telescope are presented in some detail. The cost is estimated using the assumptions and procedures listed in chapter 9 of the TDR. As stated there, cost of components are taken, in descending priority, from industrial quotations, corresponding costs as occurred in the pilot projects, public catalogues and informal or confidential statements of providers.



v 20111031			KM3NeT with DOM-towers			
			Cost per item [€]	*Nr. Of items*	*Total cost [€]*	*% total cost*
Infrastructure			***35400000***	***1***	*35400000*	***16%***
	Shore station		13000000			
	Deep-sea network		22400000			
Deployment			***30000000***	***1***	*30000000*	***13%***
Detection Unit Infrastructure			***109800***	***320***	*35136000*	***16%***
	DU Mechanics		39800			
		storeys				
		base				
		buoy				
		buoy frame				
		anchor				
		ropes				
		spacer storeys				
	Connection to network		20000			
	Backbone cables		40000			
	DU electronics		10000			
DOM infrastructure			***3555***	***12800***	*45504000*	***20%***
	Glass sphere		400			
	Electronics		2160			
		DOM logic				
		e/o convertor				
		Octopus				
		Power conversion				
	DOM mechanics		120			
		Foamcore				
		Silgel				
		Tape				
		Putty				
	Cooling		115			
		Shield				
		Bar				
		Silgel				
	Instrumentation		410			
		Piezo				
		Nanobeacon				
		Compass+Tilt				
		Pressure gauge				
		Glue				
	Penetrator		300			
	Mechanical interface to DU		50			
PMT unit			***195***	***396800***	*77376000*	***35%***
Total KM3NeT					*223416000*	*100%*

Table 12 Breakdown estimated investment cost for KM3NeT with 320 DOM-towers.



v 20111031			KM3NeT with DOM-strings			
			Cost per item [€]	Nr. Of items	Total cost [€]	% total cost
Infrastructure			39880000	1	39880000	18%
	Shore station		13000000			
	Deep-sea network		26880000			
Deployment			30000000	1	30000000	13%
Detection Unit Infrastructure			50125	640	32080000	14%
	DU Mechanics		5125			
		storeys				
		base				
		buoy				
		buoy frame				
		anchor				
		ropes				
		spacer storeys				
	Connection to network		20000			
	Backbone cables		20000			
	DU electronics		5000			
DOM infrastructure			3555	12800	45504000	20%
	Glass sphere		400			
	Electronics		2160			
		DOM logic				
		e/o convertor				
		Octopus				
		Power conversion				
	DOM mechanics		120			
		Foamcore				
		Silgel				
		Tape				
		Putty				
	Cooling		115			
		Shield				
		Bar				
		Silgel				
	Instrumentation		410			
		Piezo				
		Nanobeacon				
		Compass+Tilt				
		Pressure gauge				
		Glue				
	Penetrator		300			
	Mechanical interface to DU		50			
PMT unit			195	396800	77376000	34%
Total KM3NeT					224840000	100%

Table 13 Breakdown estimated investment cost for KM3NeT with 640 DOM-strings.

Estimated investment cost of the KM3NeT neutrino telescope						
v 20111031			KM3NeT with single-PMT OM towers			
			Cost per item [€]	*Nr. Of items*	*Total cost [€]*	*% total cost*
Infrastructure			***35400000***	***1***	***35400000***	***15%***
	Shore station		13000000			
	Deep-sea network		22400000			
Deployment			***30000000***	***1***	***30000000***	***12%***
Detection Unit Infrastructure			***95900***	***320***	***30688000***	***13%***
	DU Mechanics		50900			
		storeys				
		base				
		buoy				
		buoy frame				
		anchor				
		ropes				
		spacer storeys				
	Connection to network		20000			
	Backbone cables		20000			
	DU electronics		5000			
Single-PMT OM Storey infrastructure			***10450***	***6400***	***66880000***	***27%***
	Container for electronics		2000			
	Storey electronics		2300			
		storey logic				
		hydrophone electronics				
		e/o conversion				
		power conversion				
	Cooling and support		100			
	Instrumentation		1050			
		Hydrophones				
		compass+tilt				
	Connectors		1100			
	Storey cables		3900			
OM infrastructure			***714***	***38400***	***27417600***	***11%***
	Glass sphere		350			
	OM mechanics		60			
		Silgel				
		Tape				
		Putty				
	Instrumentation		54			
		Nanobeacon				
		Pressure gauge				
	Penetrator		150			
	Mechanical interface to DU		100			
PMT unit			***1380***	***38400***	***52992000***	***22%***
Total KM3NeT					***243377600***	***100%***

Table 14 Breakdown estimated investment cost for KM3NeT with 320 single-PMT OM towers.

Appendix B: List of possible threats to the project

Below is presented a preliminary list of threats. This is still to be improved in an iterative procedure inside the consortium. Probabilities of occurrence of the threats and their impact on the project are also still subject to evaluation inside the consortium.

Technical Risks		
External risks in project	Context	Emergence of new technologies calling into question previous choices
		Instability in needs, requirement & constraints
		Misreading or instability of interfaces
		Constraint
		Relations with other developments
		Uncertainty on feasibility, heterogeneity of system components
		High size of the system, instability of system architecture
		Specifications : incomplete, inadequately precised or too ambitious
		Complexity or high size of the system to be done
	Definition	Impossibility of realisation of Technical elements of interface
		Bad expression of need, Lack in supplies identification
		Change of need after the beginning of the project
		Bad interpretation of requirements (Dependability included)
		Complicated or innovative technology with lack of control and to be developed
Internal Risks in project	Design	Lack of scenario studies (technical options)
		Complexity of technical solutions
		Out-of-date technical solutions
		Change in system architecture
		Lack of technical standards
		Is the specified development time correct?
		Difficulty to reach performances (including margins)
		Omission of interfaces with other systems or projects
		Insufficient take of exploitation contraints into account. Lack of technical data.
		Uncertain report of states (inventory, as build…).
		Lack of technical maturity of the project
		Reliability of components or objects (components: unreliable, identified critical by AMDEC, under wear, for which burn is impossible…)
	R&D activity & prototypes	Object or element feasability (no validation or forbidden, not measurable after integration, for which process is delicate, with no guarantee on durability, limitation in manufacturing, implementation or control)
		Other risks on elements (long time for supply, with high impact, with short life-time, with unique supplier, vulnerable to transport, under periodic maintenance, under exploitation license)
		New technologies chosen in and of itself (technologies never used before, immatured or exotic). Use of "at the limit" technlogies.
		Obsolescence of programs
		Incompatibility of updates
		Use of proprietary softwares
		Potential obsolescence of components
		Difficulties to demonstrate/justify performances of technical choices, adequation with validation and justification methods
		High technological risks (innovative technical solutions but with no industrial validation)
		Missing data related to process or product studied
		High level of innovation, late development verification
	Logistics	Late take of construction site organization, lack of storage areas, long supply time, deterioration in transport between laboratories and experiment sites
		Weakness of components or systems
		Difficulties to transport some components, equipements without possible substitution.

	Realisation	Non-conformity
		Lack of qualification tests
		Key points badly defined
		Difficulties to make tests
		Bad definition of control plans
		Impossibility to validate sub-assemblies before assembly
		Expensive tests, Late controls
		Assembly and integration externalised (not done by consortium)
	Exploitation	No appropriation of exploitation data
		Use of complicated softwares
		Forgotten maintenance
Programmatic Risks		
External risks in project	Politic/Strategic	Lack in strategic analysis
		Instability of need
		Uncertainty on long-term programs
		Interfaces between programs (impact of changes in other programs)
		People or group of people with different scientifical & technical levels put neck and neck
		A team or a laboratory might call for or be forced tasks for which they not have needed competences.
	Legal/Regulatory	Lack of regulation
		Lack of standard
		Patent difficulties
		European regulation (Health…)
		Contradiction between countries regulations
		Changes in regulation standards
		Different understandings of standards
		Drift of instruction time for safety or security files
	Industiral Politics	Contraints related to partners
		Unavailability of partner's technical means
		Project has not prioritory for partner
		Architecture is not optimised
		Incompatibility between official regulation and some practices in industry (terms for payement) Comment: This could prevent project from some industrial support, which would respond to our needs.
	Organizational	Customer is not well known
		Long time to take a decision
		Confusion between roles of client, project manager (general contractor), contracting owner counseling, project manager delegate
		Lack of representative
		Shortcircuit in process of decision taking
		Possible changes in project organisation
		Industrial strifes : impossibility to access to equipment in a firm, an experiment.
		Future user : Missing or unexperienced representative. Bad acceptation of change
		No experience and/or training to project management, for some big projects responsibles
	Financial	Lack of multi-annual agreement
		Financial trade-off are not in favor of the project
		Economical state of customer
		Financial constraints of supervision authorities
		Complexity of financal architecture
		Cost or time objectives are too ambitious
		Financial deficiency of a partner
	Media	Project acceptability (public debate, publique poll, survey)
		Many decision-making interferences
	Environment	Aggressions from earth (earthquake, mudslide, various falls, geotechnics, volcano), water (flood), air (climate, frost, wind, bad weather, lightning)
		Plane, road, rail traffic, and from surrounding industries

		Man, source of danger (interactions with neighbourhood)
	Logical sequence	Bad definition forgotten tasks, roles and responsibilities. Responsibilities are no defined between subsystems
		Mistakes of evaluation over the sequence of tasks
		An interface is not totally treated
	Project management	Lack of tools, means ; insufficient scheduling and organization
		Lack of reporting or indicators
		Insufficient scheduling or work organization
		Insufficient margin : cost, time, performances
		Knowledge management / Know-How
		Decisional shortcircuit
		Bad diffusion of information
		Configuration management / Differences between documentation and products
	Performance management	No performance management plan
		Bad identification of technical performances at the beginning of the project, bad control at the end
		Missing or bad definition, or bad timing of conceptual reviews
		No prototype
	Organisational/Resource	Differences between physicists and engineers points of view are complementary ; but sometimes they could be at the opposite.
		High level of turn over (during project, departure and/or mobility of people with crucial know-how ; it's not easy to substitute them regarding human resource management in publique administration)
		Incompatibility between groups or persons
		Role and responsibilities are not well defined. Complexity of project organization. High number of implied actors
		Hard mobilisation of human resource
		Long duration of procurement
		Bad definition of criterions for the selection of suppliers. Too late implication of support actors (jurists, buyers, controllers, purchasing agents, project management)
		Lack of resources. Lack of experience of project team. Unqualified resources (to make some equipments ; due to little flexibility in human resources management ; laboratories could devote people to tasks for which they have nobody or not trained people)
		Loss of skills (mobility, retirement)
		Hazards and their related provision are not taken into account
Internal Risks in project	Budget	Funds for travellings insufficient or not well-managed could lead to restrictions for travelling at crucial time for communication between collaboration members.
		Lack of reliability in financial forcasts. Lack of data to make budgets. Impossibility to attribute funds for some parts of the project.
		Difficult sprinkling in financial plan
		Difficulties to do financial realigment
	Contractual/Legal	Bad legal management of contracts (missing legal articles)
		Validity of first evaluations
		Changes of rules in program management
		Clarity and completeness of contracts
		Long duration for procurement (CCM)
		Bad definition of criterions for the selection of suppliers.
		Cost management
		Reporting, "fait accompli" politics
		Insufficient knowledge of regulations (collaboration between several countries : differents in standards and regulations - if this is not identified and solved at the beginning of the project, issues will occured)
		Forgetting or bad coverage of insurances
	Safety	Late descovery of security requirements ; technical solution reappreasal for security ; lack of communication with security authorities ; lack of demonstration

		Actors of control and safety are not implied or too late.
		Fire (Heat source, flammable products or materials)
		Insufficient means. Accidents on the experiment site.
		Mechanical aspects (pressurized equipments, elements under mechical contraints, elements in motion, elements with needs of handling)
		Source of physical explosion other than pressurised equipment, high vaccumed volum, explosive gas
		Source of falling, of tumbling, and other source of injuries
		Electrical origin (direct or alternative current, medium and high voltage, electro-statiscme, power capacitors, high frequencies)
		Thermal and radiation hazards (ionizing radiation, thermal sources - burn, laser, microwaves, magnetic fields)
		Biological hazard (Virus – Bacteria - Room with controled moisture - Toxins)
		Man, source of danger (operator)
		Work station, source of danger (design of work station)
	Suppliers/ Manufacturers	Differences between physicists and engineers points of view are complementary ; but sometimes they could be at the opposite.
		Complete failure of a sub-contractor : bankrupt, stop of activity
		"Partial" Failure of an industrial subcontractor: non-conformance of product
		%(revenue of project)/(global revenue)
		Turn over
		Expected contribution is not contractualized ; conflict between priorities (lack of reactivity, commitment, resources…)
		Borderline of suppliers (knowledge, skills, availability)
		Insufficient contacts
		Work load is under estimated
		Means of production / control / test
		Knowledge of the program team
		Appropriateness of industrial architecture
		Market situation : monopolistic situation, low competition.
		Change of the situation (Production cycles of scientific equipments are very long. Components, specified and validated at the beginning of the project, could not be produced anymore at the beginning of the production)