Water optical properties of deep sea sites in the Mediterranean

The NEMO Collaboration

December 11, 2002

Starting from 1998 the NEMO collaboration has conducted several oceanographic campaigns in the Mediterranean Sea in order to select and characterize an optimal submarine site for the installation of a km^3 underwater neutrino telescope.

At the beginning of this activity three areas close to the Italian Coast have been selected, each one fulfilling the requirements of having a depth greater than 3000 m and a distance from the coast not larger than 100 km. Two of these areas are located in the Tyrrhenian Sea near the Island of Alicudi and Ustica. The third one is a wide and flat region extended from 40 km to 80 km SE offshore Capo Passero (Sicily).

Campaigns of measurements have also been carried out, using the instrumentation of the NEMO collaboration, in Lake Baikal (Siberia), where the Baikal-NT200 telescope is deployed, and in the site selected by the ANTARES collaboration for the installation of the 0.1 km^2 telescope (40 km SE offshore Toulon, France). Meanwhile the collaboration investigated the optical properties of the Test Site, selected for the installation of prototypal structure of the km^3 detector, that is located 25 km East offshore the port of Catania. Coordinates of the investigated sites are quoted in Table 1.

In this work we report, site by site, on the measurements of absorption and attenuation coefficients with the aim of comparing the optical properties of these sites and demonstrate the validity of the choice of Capo Passero as a preferred site for the installation of the km^3 Mediterranean telescope.

Site	*Latitude*	*Longitude*	*Depth*	*Distance from coast*
Alicudi	38° 56' N	14° 16' E	3500 m	25 Nm
Ustica	38°55’ N	13°18’ E	3500 m	15 Nm
Capo Passero (KM4)	36° 16’ N	16° 06' E	3350 m	40 Nm
Capo Passero (KM3)	36° 30’ N	15° 50' E	3350 m	20 Nm
NEMO Test-Site	37° 33.36' N	15° 22.36' E	2000 m	12 Nm
ANTARES Site	42° 50' N	06° 05' E	2400 m	20 Nm
Baikal Site	51° 50' N	104° 20' E	1200 m	1÷2 Nm

Table 1 - Coordinates of the investigated abyssal sites.

Optical properties of deep sea waters

Optics in deep sea

The study of optical properties in the selected site is extremely important and must be completed with a long term program of characterisation carried out in all different seasons. Seawater, indeed, absorbs and scatters photons as a function of water temperature, salinity and concentration, dimension and refraction index of dissolved and suspended, organic/inorganic particulate. These parameters are different in different marine sites and change as a function of time. Since water temperature, salinity and particulate concentration may vary significantly in different marine sites, and also as a function of time, it is important to measure optical parameters *in situ*. In order to describe the transparency of natural waters, as a function of photon wavelength, it is therefore necessary to measure *in situ* the so called *Inherent Optical Properties* (IOP) of the water, such as the absorption $L_a(\lambda)$, scattering $L_b(\lambda)$ and attenuation $L_c(\lambda) = [L_a(\lambda) \cdot L_b(\lambda)]/[L_a(\lambda) + L_b(\lambda)]$ lenghts [1].

Each of these lengths represents the path after which a photon beam of intensity I_0 and wavelength λ travelling along the emission direction, is reduced of a factor 1/e by absorption or diffusion phenomena. These quantities can be directly derived by the simple relation:

$$I_{a,b,c}(x) = I_o \exp(-x \cdot L_{a,b,c})$$

where x is the optical path traversed by the beam and I_0 the source intensity. In the literature the absorption $a = 1/L_a$ and the scattering $b = 1/L_b$ coefficients are extensively used to characterize the light transmission in matter. The sum of scattering and absorption coefficients is called attenuation coefficient $c(\lambda)$.

In pure water, light absorption and scattering are strongly wavelength dependent. In particular light transmission in pure water is extremely favored in the range 350-550 nm, overlapping the region in which photomultiplier tubes usually reach the highest quantum efficiency. In the visible region of the electromagnetic spectrum light absorption steeply decreases as a function of wavelength and reaches its minimum at about 420 nm [2]. Scattering refers to processes in which the direction of the photon is changed without any other alteration. Scattering phenomena in which the photon wavelength changes (e.g. Raman effect) happen less frequently. Scattering can take place either on molecules (Rayleigh scattering) or on dissolved particulate (Mie scattering).

Another parameter commonly used in the literature is the effective scattering length $L_b^{eff} = L_b(\lambda)/[1 - \langle \cos(\theta) \rangle]$, where $\langle \cos(\theta) \rangle$ is the average cosine of the scattering angle. The estimation of the last parameter is extremely difficult since it needs the knowledge of another IOP, the volume scattering function $\beta(\theta,\lambda)$, that must be measured with appropriate devices [3].

Instrumentation used by the NEMO Collaboration

Light attenuation and absorption measurements in deep seawater were performed by means of a set-up based on a commercial trasmissometer: the *AC9* manufactured by Wetlabs [4]. The device compactness (68 cm height × 10.2 cm diameter) and its pressure resistance (it can operate down to 6000 m depth) are excellent for our purposes. The *AC9* performs attenuation and absorption measurements independently, using two different light paths and spanning the light spectrum over nine different wavelengths (412, 440, 488, 510, 532, 555, 650, 676, 715 nm). Following an accurate calibration procedure we obtained an accuracy in $a(\lambda)$ and $c(\lambda)$ of about $1.5 \cdot 10^{-3}$ m^{-1}. Using *AC9* data, the scattering coefficient can be calculated subtracting the absorption coefficient value from the attenuation coefficient one at each given wavelength. During deep sea measurements we connect the *AC9* to a standard oceanographic CTD (Conductivity–Temperature–Depth) probe: the Idronaut Ocean MK317. The instruments are assembled on an AISI-316 stainless-steel cage before a deployment. The DAQ set-up is designed to acquire the *profiles* of a set of 20 parameters that characterise the water column (temperature, salinity, nine absorption coefficients and nine attenuation coefficients) as a function of depth. In order to estimate systematic errors at least two profiles at short time distance (~ 6 hours) were carried out in each site. Further details about the measurement procedure and data analysis can be found in [5].

Optical properties of the sites close to the Italian Coast

The Tyrrhenian Sea: Ustica and Alicudi

The bathimetric profile of the Southern Tyrrhenian Sea shows several abyssal planes (depths ~3500 m). The NEMO collaboration has identified two possible sites of interest offshore the northern Sicilian coast: the first one is less than 50 km NortWest of Alicudi Island, the second one is ~30 km NortEast of Ustica Island.

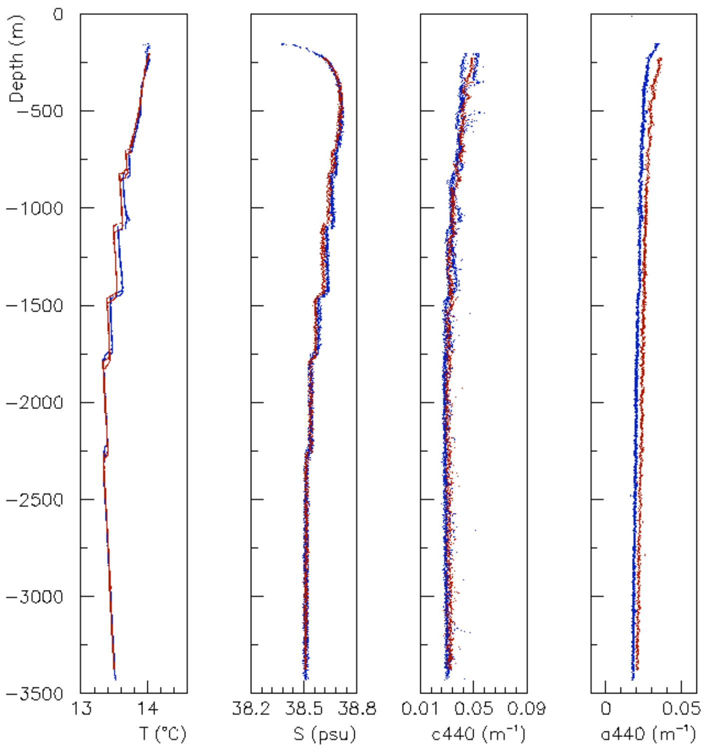

Figure 1 – Profiles, as a function of depth, of the temperature (T), salinity (S), attenuation (c) and absorption (a) coefficients measured in the sites of Ustica and Alicudi. Each point represents the average value over 6 measurements. The dispersion for c is grater than in a due to the dependence on the local concentration of scattering centers (dissolved particulate).

The optical properties of the two sites have been studied during an oceanographic campaign which took place onboard the *R/V Urania*, in collaboration with Istituto di Oceanografia Fisica – CNR (La Spezia, Italy), during December 1999. Data collected during this campaign have been already published [5].

Two profiles of the water column have been carried out in each site. In figure 1 we report, as a function of depth, sea temperature, salinity and the values of a and c coefficients for $\lambda = 440$ nm. Data measured in Alicudi and Ustica are plotted in blue and red, respectively. The "layer"-like profile, typical of the Tyrrhenian Sea, well studied by oceanographers in terms of temperature and salinity [6], is slightly evident also in the variability of the light attenuation coefficient. The water column becomes more homogeneous at depths greater than 2500 m.

In tables 2 and 3 we report, as a function of the wavelength, the absorption and attenuation coefficients measured during the four deployments. The quoted values refers to depth greater than 2850 m. In the same tables we report also, for each site, the average value of the measurements. Values of a and c for the 488, 532 and 555 nm wavelengths have been omitted, due to an imperfection of the instrument filter found after the measure and repaired after. The statistical error associated is negligible. Systematic errors have been estimated to be of the order of $\sigma_{a,c} \simeq 2.0 \times 10^{-3}$ m^{-1} for all the wavelengths.

Ustica and Alicudi absorption coefficients (December 1999)

λ (nm)	***Ustica 1st profile***	***Ustica 2nd profile***	***Ustica average***	***Alicudi 1st profile***	***Alicudi 2nd profile***	***Alicudi average***
412	0.023	0.020	0.021	0.018	0.018	0.018
440	0.022	0.019	0.020	0.018	0.018	0.018
510	0.039	0.038	0.038	0.038	0.038	0.038
650	0.357	0.358	0.357	0.356	0.357	0.356
676	0.444	0.444	0.444	0.444	0.444	0.444
715	1.016	1.016	1.016	1.016	1.017	1.016

Table 2 – Absorption coefficients a(λ), averaged over depths greater than 2850 m, measured in Ustica and Alicudi in December 1999. We report, for each site, also the average value of the two deployments.

Ustica and Alicudi attenuation coefficients (December 1999)

λ (nm)	***Ustica 1st profile***	***Ustica 2nd profile***	***Ustica average***	***Alicudi 1st profile***	***Alicudi 2nd profile***	***Alicudi average***
412	0.036	0.032	0.034	0.033	0.033	0.033
440	0.031	0.029	0.030	0.030	0.030	0.030
510	0.040	0.042	0.041	0.041	0.041	0.041
650	0.376	0.378	0.377	0.376	0.378	0.377
676	0.447	0.445	0.446	0.446	0.445	1.445
715	1.017	1.017	1.017	1.017	1.017	1.017

Table 3 - Attenuation coefficients c(λ), averaged over depths greater than 2850 m, measured in Ustica and Alicudi in December 1999. We report, for each site, also the average value of the two deployments.

Capo Passero

The region of interest is a wide marine area located at distance of 40÷80 km SouthEast of Capo Passero that presents low values of current intensity (~3 cm/s) and low biological activity. The bathymetric profile is flat over hundreds km^2 with an average depth of ≈3350 m. The first measurements of optical parameters reported here have been carried out in December 1999, onboard the oceanographic vessel *Urania*, in collaboration with the Istituto Sperimentale Talassografico, CNR (Messina, Italy). During the campaign the collaboration carried out also biochemical analyses of the water column, recovery and deployment of current meters and sediment traps, four deployments of the *AC9*.

Two profiles have been carried out in a site 20 NM South East of Capo Passero, named KM3, which has a depth of 3350 m. Other two profiles have been carried out in site KM4 (depth 3350 m), 40 NM South East from the coast.

Figure 4 shows as a function of depth, the value of temperature, salinity, $a(\lambda=440$ nm) and $c(\lambda=440$ nm) measured in the two sites (KM3 blue dots, KM4 red dots). At depth larger than 1250 m the water column in KM4 shows homogeneous optical and oceanographic properties. Moreover compared to KM3, which is closer to the Malta Escarpment, KM4 has better optical properties, especially for the attenuation coefficient. These differences, together with other considerations like the greater distance from the shelf break, lead the collaboration to prefer the KM4 site for successive characterization of the region of Capo Passero.

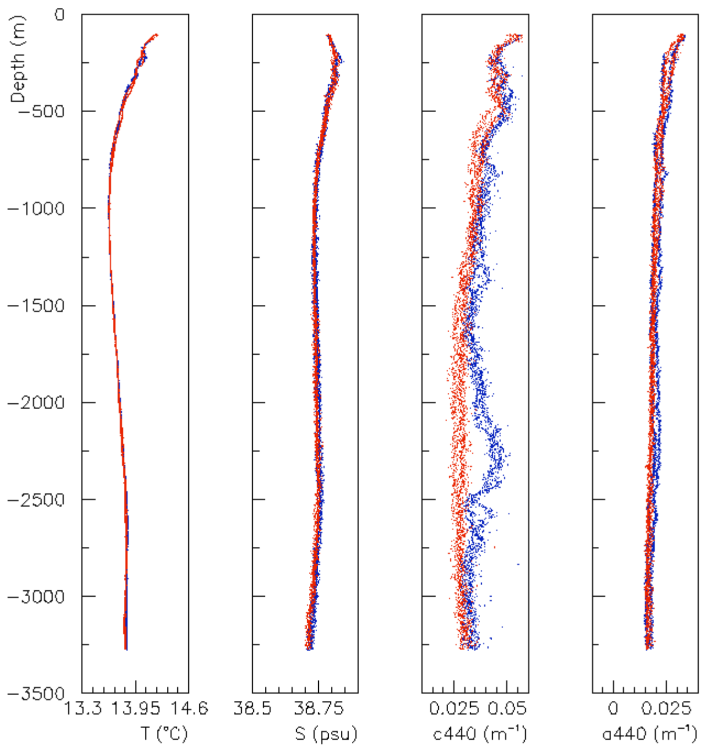

Figure 4 - Comparison between the profiles of T, S, c(440), a(440) measured in KM3(blue) and KM4(red).

In tables 4 and 5 we report respectively the average values of the coefficients $a(\lambda)$ and $c(\lambda)$ measured at depth larger than 2850 m during the four deployments in the region. In this case also we omit the values recorded at λ = 488, 532 e 555 nm.

Capo Passero KM3 and KM4 Sites absorption coefficients (December 1999)

λ(nm)	*KM4 1st profile*	*KM4 2nd profile*	*KM4 average*	*KM3 1st profile*	*KM3 2nd profile*	*KM3 average*
412	0.014	0.015	0.014	0.017	0.014	0.015
440	0.016	0.017	0.165	0.018	0.016	0.017
510	0.036	0.037	0.036	0.037	0.037	0.037
650	0.356	0.358	0.357	0.356	0.356	0.356
676	0.444	0.444	0.444	0.444	0.444	0.444
715	1.017	1.017	1.017	1.016	1.017	1.016

Table 4 - Absorption coefficients $a(\lambda)$, averaged over depths greater than 2850 m, measured in KM3 and KM4 in December 1999. We report, for each site, also the average value of the two deployments.

Capo Passero KM3 and KM4 Sites attenuation coefficients (December 1999)

λ(nm)	*KM4 1st profile*	*KM4 2nd profile*	*KM4 average*	*KM3 1st profile*	*KM3 2nd profile*	*KM3 average*
412	0.031	0.034	0.032	0.036	0.034	0.035
440	0.028	0.029	0.028	0.034	0.031	0.032
510	0.040	0.043	0.041	0.044	0.042	0.043
650	0.372	0.375	0.373	0.378	0.374	0.376
676	0.449	0.450	0.449	0.449	0.451	0.450
715	1.017	1.019	1.018	1.021	1.019	1.020

Table 5 - Attenuation coefficients $c(\lambda)$, averaged over depths greater than 2850 m, measured in KM3 and KM4 in December 1999. We report, for each site, also the average value of the two deployments.

Comparison of the Italian candidate sites

In figure 5 and 6 we show, as a function of λ, the average values of absorption and attenuation lengths measured in the four sites investigated in this phase (December 1999) of site selection activity (Alicudi, Ustica, KM3 and KM4)[1].

We show for comparison also light transmission data for optically pure water (microfiltered water) taken from [1,7]. **It is clearly observable that at all wavelengths, deep waters in KM4 have an absorption length compatible with pure water. In comparison with the other sites, KM4 also shows the best values of L_c.**

The value of the light attenuation length is obviously worse than the one measured for microfiltered water, due to the dependence on the scattering coefficient, which is a function of the concentration of scattering centres dissolved in natural waters.

[1] We show the values of $L_a(\lambda)$ and $L_c(\lambda)$ in order to allow the reader to immediately evaluate the effect of water optical properties on the detector design: granularity, number of optical sensors,...

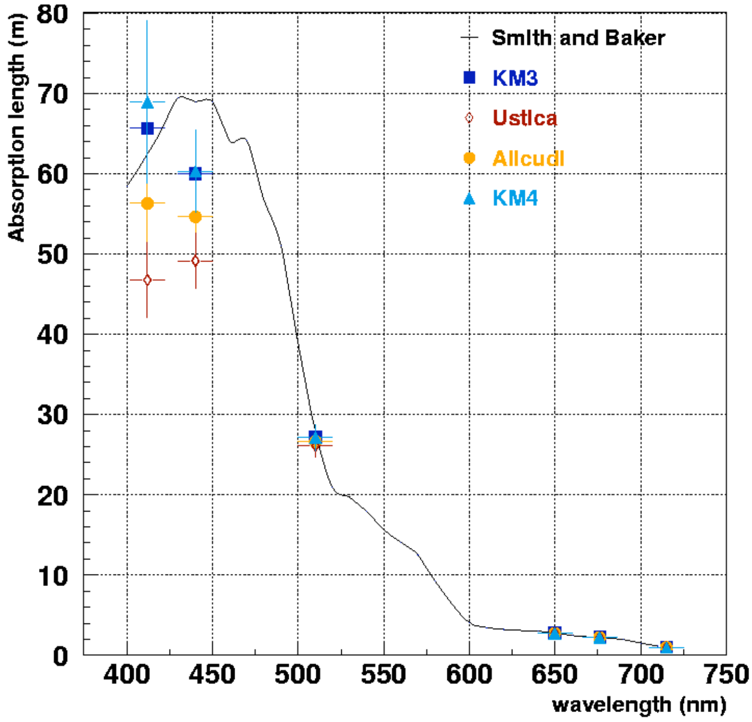

Figure 5 – Comparison between average absorption lengths, measured at depths greater than 2850 m, in KM3, KM4, Alicudi and Ustica.

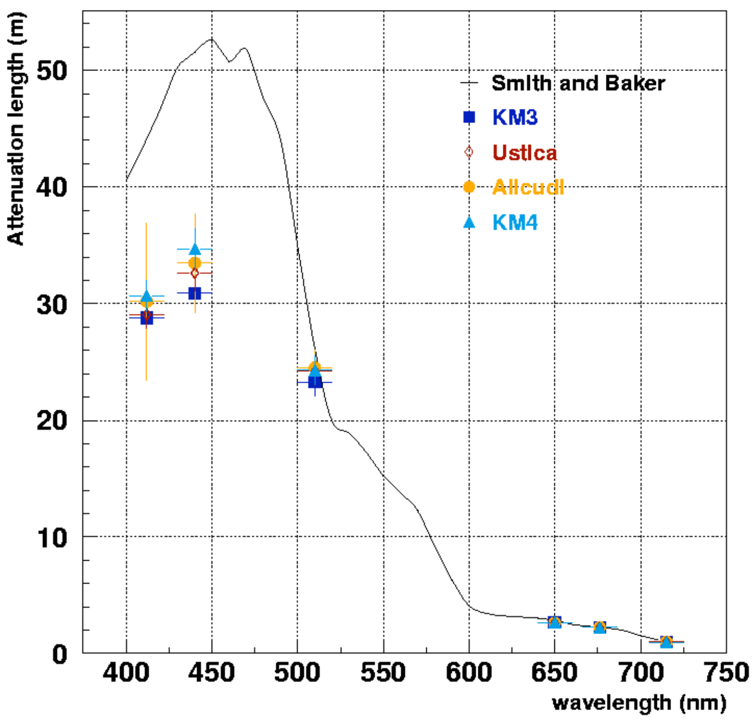

Figure 6 - Comparison between average attenuation lengths, measured at depths greater than 2850 m, in KM3, KM4, Alicudi and Ustica.

Characterisation of optical properties in Capo Passero

Having chosen KM4 as the best site among the four pre-selected, the collaboration started a series of campaigns aiming at studying the temporal behaviour of optical properties in KM4. In the same campaigns the collaboration carried out several multiparametric analyses intended to characterise the oceanographic properties of the site. Since August 2001 a mooring, equipped with two current meters and a sediment trap to study the variability of currents, temperature, salinity and sedimentation as a function of time, is deployed in KM4. From December 1999 to February 2000 the collaboration deployed a deep sea station for the measurement of biofouling. Measurements of optical background due to ^{40}K and bioluminescence have been also carried out.

In particular during 2002 the Collaboration has performed three campaigns in KM4, in order to verify the occurrence of seasonal effects in optical properties. It is expected, in fact, that during months of major biological activity the concentration of dissolved and suspended particulate increases, worsening water transparency. The results of these campaigns are reported in the following.

Mission March 11-18, 2002

This campaign has been carried on onboard the *R/V Urania*, in collaboration with the Istituto Nazionale di Oceanografia e Geofisica Sperimentale di Trieste (OGS) [8]. During the campaign four profiles of the water column have been performed. For three of the four deployments, the *AC9* was coupled with DEWAS (DEep WAter Scatteringmeter) a prototypal device, designed and constructed by the NEMO Collaboration, capable to measure the volume scattering function at three different wavelengths [3]. Other activities conducted during the cruise where: recovery and re-deployment of the current-meter mooring; measurements of optical background at 3000 m depth; geological analysis of the sea bed with sub-bottom profiler and collection of core samples.

In Tables 6 and 7 we report, as a function of wavelength, the average absorption and attenuation coefficients measured at depths greater than 2850 m in each deployment. We also report the average value of the four measurements.

Mission April 29 – May 1, 2002

This cruise was conducted onboard the R/V *Alliance* owned by the underwater research centre *SACLANT-Cen NATO* (La Spezia, Italy) [9]. Two water profiles have been carried out in KM4 using the *AC9*.

The average values recorded in the two deployments are quoted in Tables 8 and 9.

Mission August 9-17, 2002

The cruise was conducted onboard the *R/V Alliance*, in collaboration with the optical measurements group of the ANTARES collaboration, the OGS and with the CIBRA (Consorzio Interdisciplinare di Bioacustica e Ricerche Ambientali, Pavia, Italy). Three *AC9* deployments have been carried out. In the same cruise the ANTARES group operated two deployments of their device TEST-3' used for measuring water absorption and effective attenuation at large depth [10]. Measurements of optical noise have been carried out by the two groups. NEMO recovered and re-deployed the current metre mooring in KM4.

In Tables 10 and 11 we report, as in previous paragraphs, the average values of $a(\lambda)$ and $c(\lambda)$ measured by the AC9 and averaged for depths greater than 2850 m.

Capo Passero KM4 Site absorption coefficients (March 2002)

λ (nm)	***1st profile***	***2nd profile***	***3rd profile***	***4th profile***	***Average***
412	0.021	0.020	0.020	0.019	0.020
440	0.016	0.015	0.016	0.015	0.015
488	0.018	0.018	0.018	0.018	0.018
510	0.037	0.037	0.037	0.037	0.037
532	0.051	0.052	0.053	0.052	0.052
555	0.068	0.068	0.068	0.068	0.068
650	0.360	0.361	0.362	0.361	0.361
676	0.444	0.444	0.444	0.444	0.444
715	1.046	1.045	1.046	1.045	1.045

Table 6 - Absorption coefficients a(λ), averaged over depths greater than 2850 m, measured in KM4 in March 2002. The average value of the four measurements is also reported.

Capo Passero KM4 Site attenuation coefficients (March 2002)

λ (nm)	***1st profile***	***2nd profile***	***3rd profile***	***4th profile***	***Average***
412	0.038	0.033	0.031	0.031	0.033
440	0.032	0.028	0.026	0.027	0.028
488	0.026	0.024	0.022	0.024	0.024
510	0.045	0.042	0.040	0.042	0.042
532	0.061	0.058	0.056	0.058	0.058
555	0.079	0.075	0.073	0.075	0.075
650	0.385	0.379	0.377	0.380	0.380
676	0.475	0.468	0.466	0.468	0.469
715	1.064	1.059	1.058	1.059	1.060

Table 7 - Attenuation coefficients c(λ), averaged over depths greater than 2850 m, measured in KM4 in March 2002. The average value of the four measurements is also reported.

Capo Passero KM4 Site absorption coefficients (May 2002)

λ (nm)	*1st profile*	*2nd profile*	*Average*
412	0.017	0.019	0.018
440	0.014	0.017	0.015
488	0.017	0.019	0.018
510	0.036	0.038	0.037
532	0.051	0.052	0.051
555	0.067	0.068	0.067
650	0.361	0.361	0.361
676	0.444	0.444	0.444
715	1.046	1.046	1.046

Table 8 - Absorption coefficients a(λ), averaged over depths greater than 2850 m, measured in KM4 in May 2002. The average value of the two measurements is also reported.

Capo Passero KM4 Site attenuation coefficients (May 2002)

λ (nm)	*1st profile*	*2nd profile*	*Average*
412	0.038	0.033	0.035
440	0.031	0.026	0.028
488	0.024	0.021	0.022
510	0.047	0.042	0.044
532	0.058	0.057	0.057
555	0.084	0.080	0.082
650	0.386	0.385	0.385
676	0.477	0.475	0.476
715	1.065	1.064	1.064

Table 9 - Attenuation coefficients c(λ), averaged over depths greater than 2850 m, measured in KM4 in May 2002. The average value of the two measurements is also reported.

Capo Passero KM4 Site absorption coefficients (August 2002)

λ (nm)	*1st profile*	*2nd profile*	*3rd profile*	*Average*
412	0.020	0.021	0.021	0.021
440	0.015	0.015	0.015	0.015
488	0.018	0.018	0.018	0.018
510	0.039	0.038	0.038	0.038
532	0.051	0.050	0.050	0.050
555	0.068	0.068	0.068	0.068
650	0.362	0.362	0.362	0.362
676	0.444	0.444	0.444	0.444
715	1.046	1.046	1.046	1.046

Table 10 - Absorption coefficients a(λ), averaged over depths greater than 2850 m, measured in KM4 in August 2002. The average value of the three measurements is also reported.

Capo Passero KM4 Site attenuation coefficients (August 2002)

λ(nm)	*KM4 1st*	*KM4 2nd*	*KM4 3rd*	*KM4 average*
412	0.033	0.033	0.033	0.033
440	0.028	0.028	0.029	0.028
488	0.022	0.023	0.023	0.023
510	0.045	0.045	0.046	0.045
532	0.058	0.059	0.059	0.059
555	0.079	0.078	0.080	0.079
650	0.385	0.385	0.385	0.385
676	0.475	0.474	0.473	0.474
715	1.066	1.065	1.064	1.065

Table 11 - Attenuation coefficients c(λ), averaged over depths greater than 2850 m, measured in KM4 in August 2002. The average value of the three measurements is also reported.

Discussion on seasonal variations of optical properties in KM4

In figure 7 we show the profiles recorded with the *AC9*-CTD setup in the cruises of December 1999 (light blue), March 2002 (yellow), May 2002 (Blue) and August 2002 (red). The values of temperature, salinity and the coefficients *a*(λ) and *c*(λ) for the 440, 510 and 650 nm wavelengths are reported as a function of depth.

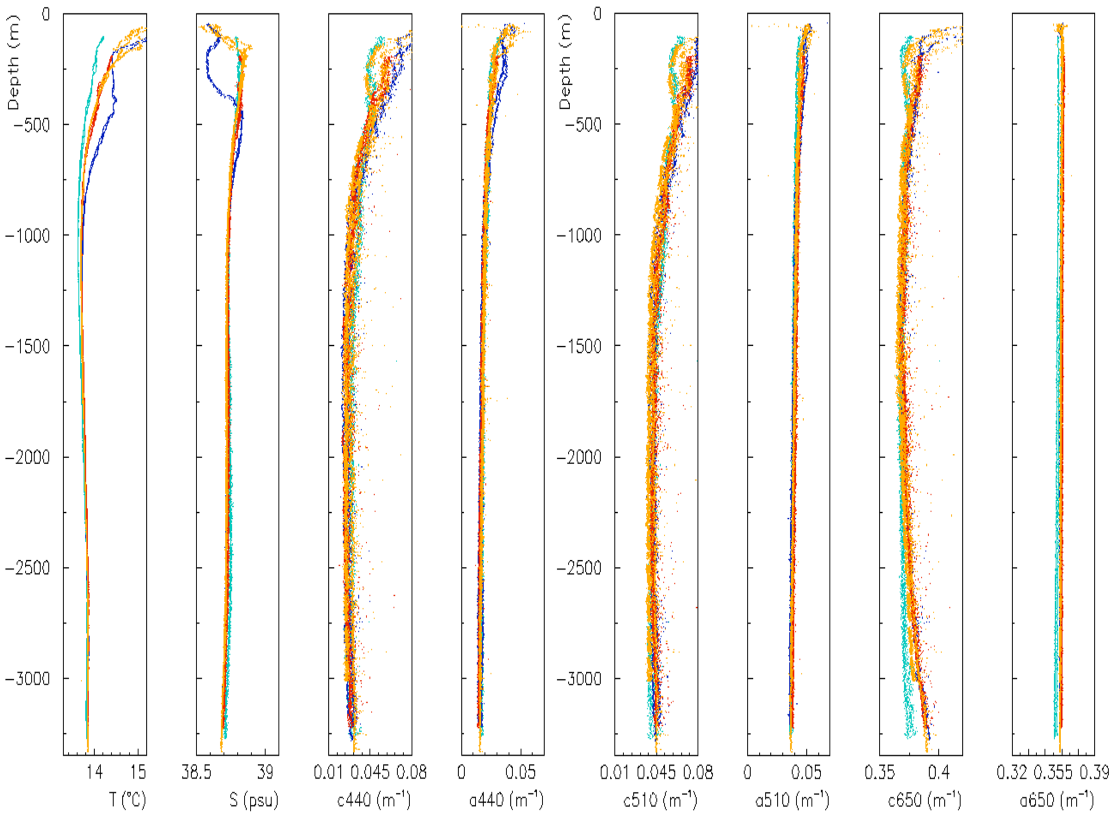

Figure 7 – Profiles of temperature (T), salinity (S), attenuation coefficient (c) and absorption coefficient (a) for variouos wavelengths, measured in the Capo Passero KM4 site. The profiles refer to different campaigns: August (red), may (blue), March (yellow) and December (light blue).

At the depths of interest for the telescope (more than 2500 m) **seasonal variations are negligible and, for blue-green wavelengths, compatible with the instrument experimental error** ($\sigma_T \sim 10^{-2}$ °C, $\sigma_S \sim 10^{-2}$ psu, $\sigma_{a,c} \sim 2\cdot 10^{-3}$ m^{-1}).

The absorption and attenuation lengths, averaged for depths greater than 2850 m, are shown, as a function of λ, in figures 8 and 9. No evidence of a seasonal dependence of the optical parameters is present. It is worthwhile to mention that the described deployments have been carried out over an area of about 10 km^2 around the point KM4 quoted in table 1.

We can therefore conclude that optical and oceanographic properties in Capo Passero KM4 are homogeneous in a large region and constant over the whole year.

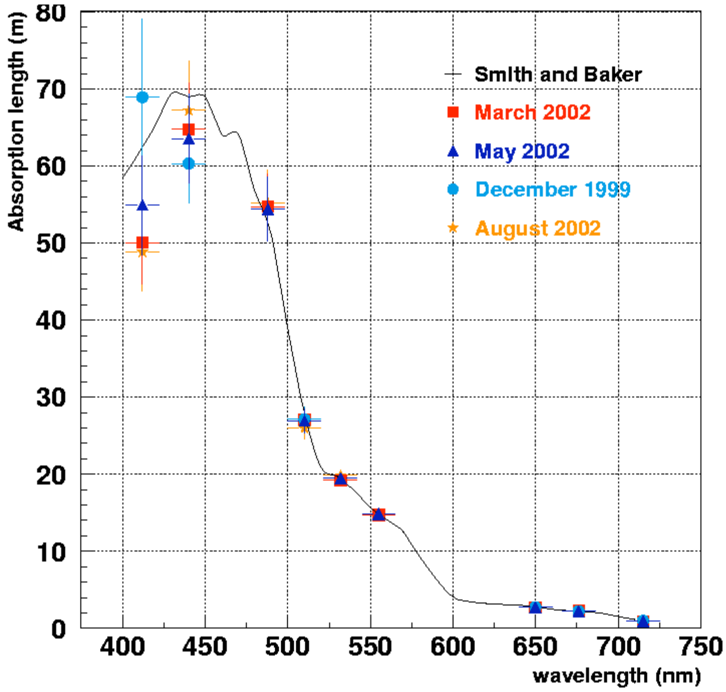

Figure 8 - Values of average absorption lengths as a function of wavelength, measured during four periods of the year in Capo Passero KM4.

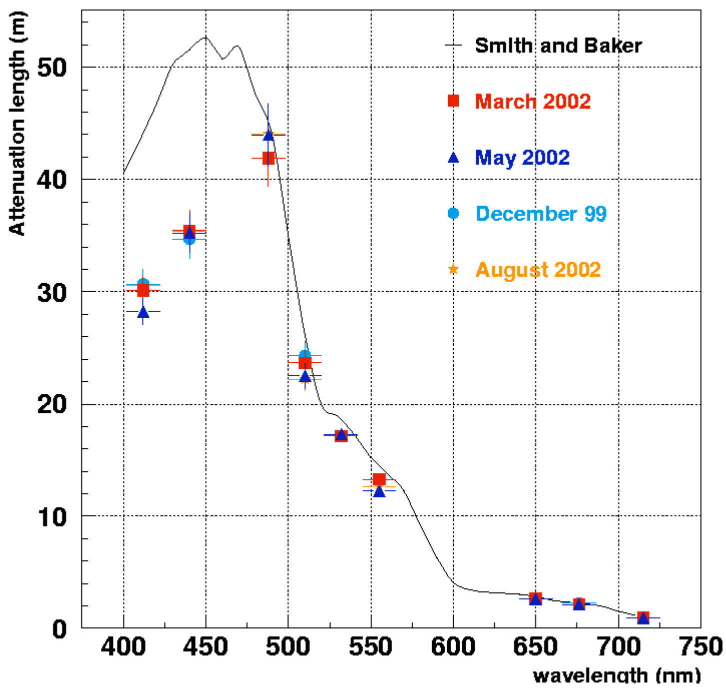

Figure 9 - Values of average attenuation lengths as a function of wavelength, measured during four periods of the year in Capo Passero KM4.

Other sites investigated by the NEMO Collaboration

The Catania Test Site

During the March and August 2002 campaigns, optical measurements at the *Test Site* of Catania, located 25 km offshore the port of Catania at a depth of about 2000 m, were also performed.

In figure 10 we show the profiles of temperature, salinity, *c*(440nm) and *a*(440nm) measured in March (yellow) and August (red). The profiles of the water column show a homogeneous behaviour at depth larger than 1500 m. Moreover, differently from KM4, the profiles are not clearly super-imposable.

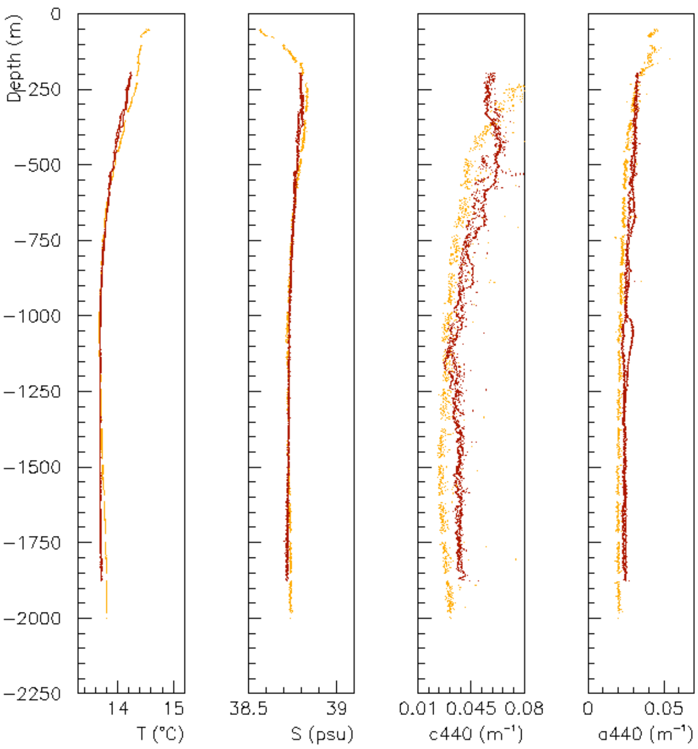

Figure 10 - Profiles of temperature, salinity, c(440nm) and a(440nm) measured in March (yellow) and August (two deployments in red) 2002 at the Catania Test Site.

A possible interpretation of this effect could be a seasonal dependence of the concentration of scattering particles. This particulate can be of organic or inorganic nature, and is characteristic of coastal waters. The Test Site is indeed localised near the Sicilian Escarpment and it is close to the Simeto River mouths. The plotted profiles could also indicate a dependence of the water column as a function of proximity to the coast. The profile recorded in March 2002 (that shows smaller coefficients with respect to August at depth >300m) was measured at 6 km more offshore than the ones recorded in August.

In Tables 12 and 13 we report the average values of *a* and *c* coefficients, measured in an interval of 300 m of depths, 150 m above the seabed. These values are clearly higher than the ones recorded in the 3000 m deep sea sites. Figures 11 and 12 show the average value of $L_a(\lambda)$ and $L_c(\lambda)$ measured in the two campaigns of March and August 2002.

Test Site absorption coefficients (March and August 2002)

λ(nm)	***March***	***August 1st***	***August 2nd***	***August average***
412	0.027	0.032	0.034	0.033
440	0.020	0.023	0.024	0.023
488	0.022	0.023	0.024	0.023
510	0.040	0.044	0.044	0.044
532	0.054	0.054	0.054	0.054
555	0.071	0.071	0.071	0.071
650	0.362	0.363	0.363	0.363
676	0.444	0.444	0.444	0.444
715	1.043	1.043	1.043	1.043

Table 12 - Absorption coefficients a(λ), averaged over the depth interval 1500-1850 m, measured in the Catania Test Site in March and August 2002. The average value of the two August measurements is also reported.

Test Site attenuation coefficients (March and August 2002)

λ(nm)	***March***	***August 1st***	***August 2nd***	***August average***
412	0.033	0.045	0.046	0.045
440	0.027	0.037	0.038	0.037
488	0.025	0.030	0.030	0.030
510	0.041	0.052	0.051	0.051
532	0.056	0.062	0.062	0.062
555	0.072	0.082	0.081	0.081
650	0.369	0.376	0.376	0.376
676	0.455	0.462	0.461	0.461
715	1.051	1.058	1.057	1.057

Table 13 - Attenuation coefficients c(λ), averaged over the depth interval 1500-1850 m, measured in the Catania Test Site in March and August 2002. The average value of the two August measurements is also reported.

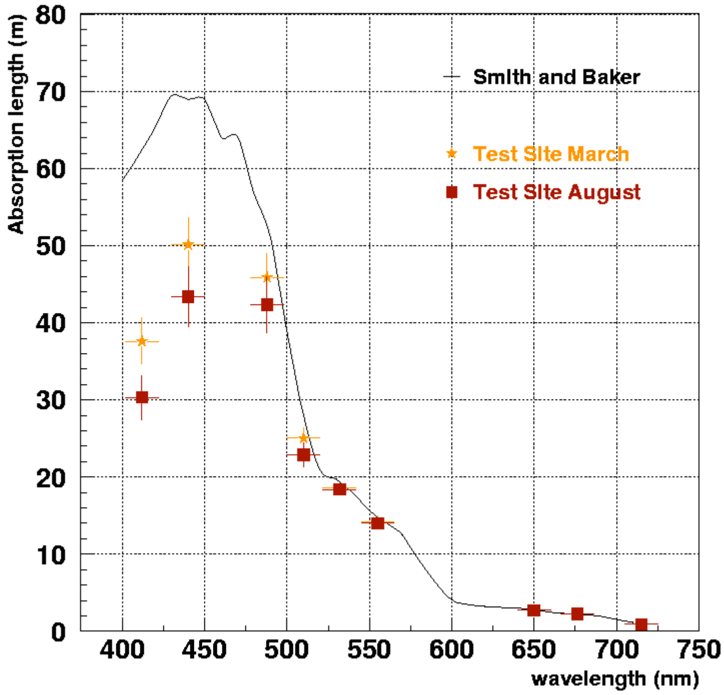

Figure 11 - Catania Test Site. Values of absorption length measured during the cruises of March (yellow star) and August (red square) 2002.

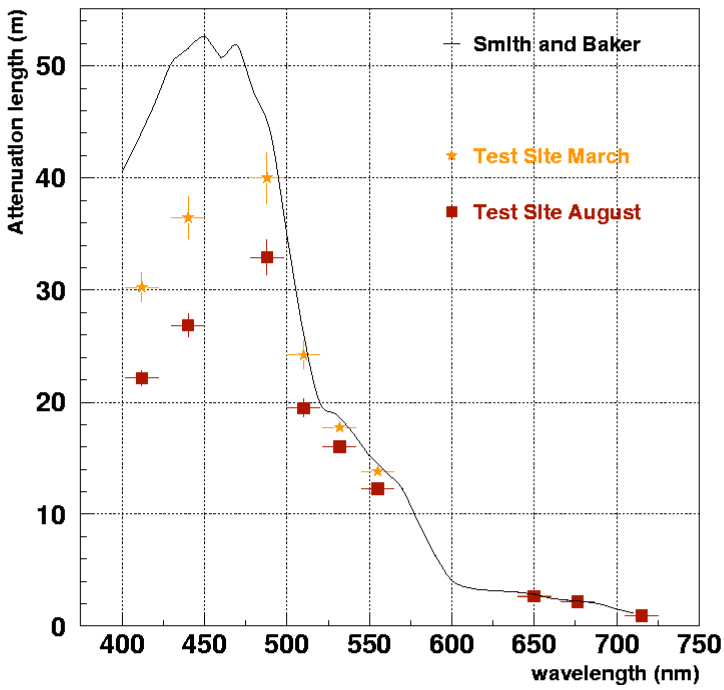

Figure 12 - Catania Test Site. Values of attenuation length measured during the cruises of March (yellow star) and August (red square) 2002.

Lake Baikal

In March 2001 the NEMO and Baikal collaboration have conducted a joint campaign to measure optical properties of Lake Baikal, where the NT-200 is deployed. The goal of the campaign was to measure light transmission in Lake Baikal simultaneously with the *AC9* and with a custom device designed and constructed by the Baikal Collaboration: the *ASP-15*. A complete report of the measurements can be found in 11].

The two profiles measured with the *AC9* (fig. 13) show an homogeneous water mass below 400 m and favorable optical properties in the interval between 900 and 1100 m depth, where the NT-200 Telescope is deployed. It should be noted that the agreement between the *AC9* and the *ASP-15* is rather good (see ref. [11] for details) and show that the systematic error associated with the measurements of $a(\lambda)$ and $c(\lambda)$ coefficients with the *AC9* is small (in the order of $1.5 \cdot 10^{-3}$ m^{-1}).

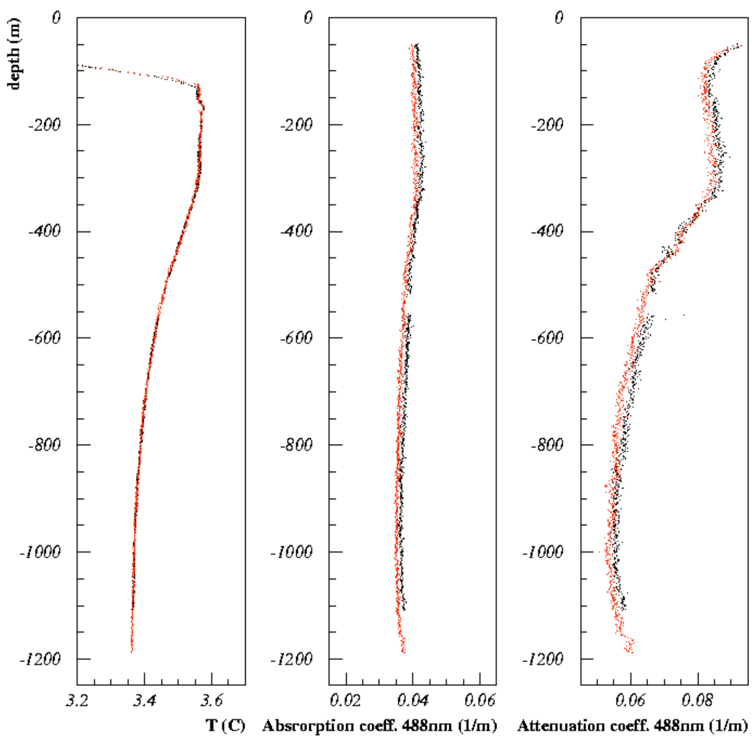

Figure 13 – Profiles of temperature, a(488) and c(488) measured in Lake Baikal in March 2001

The ANTARES site

In July 2002 the NEMO and ANTARES Collaborations have conducted a joint oceanographic Campaign, onboard the *R/V Thetis*, in order to measure the optical properties of the ANTARES site, at 2400 m depth, 20 NM SouthWest of Toulon.

During the campaign, two *AC9* profiles and two *AC9*+DEWAS profiles have been carried out by the NEMO group (figure 14). Other optical measurements have been also carried out by the ANTARES group deploying the TEST-3' device, also used during the

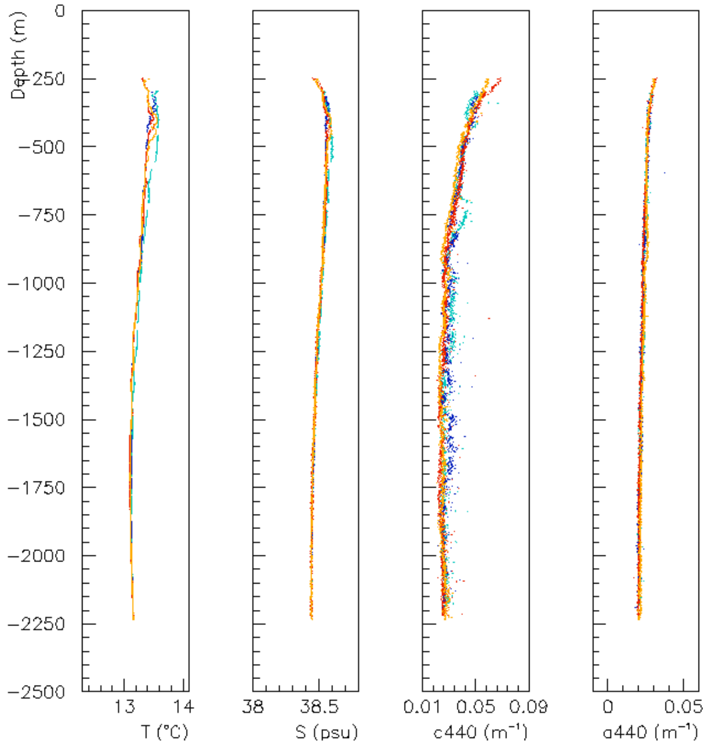

Figure 14 - The four profiles of temperature, salinity, c(440) and a(440) as a function of depth, measured with the AC9 during the cruise in the ANTARES site in July 2002.

cruise August 2002 in KM4. In the same cruise the two groups measured also the optical background at 2200 m depth with two different instruments.

The blue light attenuation coefficient profile (figure 14) obtained with the *AC9* shows a variability typical for coastal waters, down to ≈ 800 m. In Tables 14 and 15 we list the

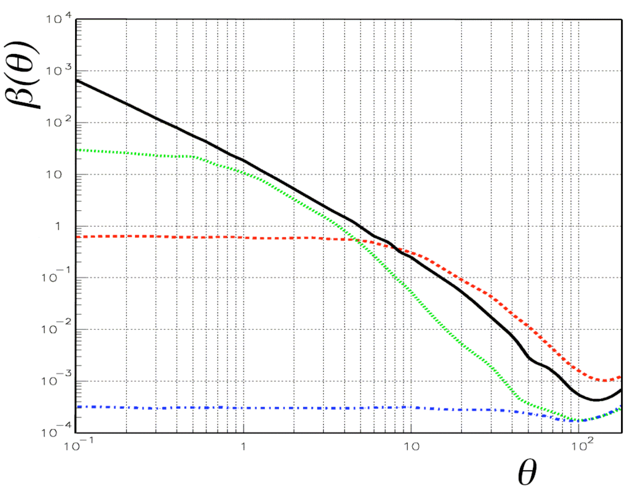

Figure 15 – Volume scattering function for pure water (Rayleigh scattering) (blue dash dotted line), Petzold coastal waters (black solid line). The red dashed line and the yellow dotted line are theoretical calculations for water samples with small and large scattering centres, respectively.

average values of $a(\lambda)$ and $c(\lambda)$ respectively, measured in the depth range 1800-2300 m, in the four deployments. The values of the absorption coefficients are larger than the ones measured in the 3000 m deep Capo Passero site, and, on the other hand, compatible with the ones measured in Catania site, which has both distance from the coast and depth similar to the ANTARES site. On the contrary the attenuation coefficients are similar to the absorption ones at each wavelength. This could imply that the density of scattering centres is extremely low. This result may be also explained in a different way. It is known from literature that waters with a large concentration of organic particulate may show a narrow forward-peaked volume scattering function (shown in fig. 15) for visible light (Petzold coastal waters [1]). In this case the AC9 angular acceptance in the *c* channel (0.7°) would be too large to discriminate between forward scattered photons and non interacting ones. The $c(\lambda)$ coefficient would be, in this case underestimated.

ANTARES Site absorption coefficients (July 2002)

λ(nm)	***1st profile***	***2nd profile***	***3rd profile***	***4th profile***	***Average***
412	0.026	0.026	0.026	0.027	0.026
440	0.021	0.020	0.020	0.021	0.020
488	0.022	0.022	0.022	0.022	0.022
510	0.041	0.040	0.041	0.041	0.041
532	0.054	0.054	0.053	0.054	0.054
555	0.070	0.070	0.070	0.070	0.070
650	0.362	0.361	0.362	0.362	0.362
676	0.444	0.444	0.444	0.444	0.444
715	1.042	1.042	1.042	1.042	1.042

Table 14 - Absorption coefficients $a(\lambda)$, averaged over the depth interval 1800-1300 m, measured in the ANTARES Site in July 2002. The average value of the four measurements is also reported.

ANTARES Site attenuation coefficients (July 2002)

λ(nm)	***1st profile***	***2nd profile***	***3rd profile***	***4th profile***	***Average***
412	0.033	0.032	0.032	0.032	0.032
440	0.027	0.026	0.026	0.026	0.026
488	0.023	0.022	0.022	0.022	0.022
510	0.042	0.041	0.041	0.041	0.041
532	0.056	0.055	0.055	0.054	0.055
555	0.075	0.073	0.074	0.074	0.074
650	0.371	0.369	0.371	0.370	0.370
676	0.458	0.457	0.458	0.458	0.458
715	1.051	1.050	1.050	1.050	1.050

Table 15 - Attenuation coefficients $c(\lambda)$, averaged over the depth interval 1800-1300 m, measured in the ANTARES Site in July 2002. The average value of the four measurements is also reported.

Comparison between sites candidates for the installation of the km^3 telescope

In figures 16 and 17 the average absorption and attenuation lengths as a function of the wavelength measured in the deep waters of the Capo Passero KM4 and ANTARES sites are compared. Even if the environmental situation is totally different, we also show in the same figure the data measured in Lake Baikal with the aim of showing the instrument sensitivity.

The first plot shows that KM4 site has blue light absorption length close to the optically pure water one [7] and considerably better than the ones measured in the other sites.

The L_a(440nm) measured in Capo Passero is 1.4 times larger than L_a(440nm) measured in ANTARES site and 3 times larger than L_a(440nm) measured in Lake Baikal.

Figure 17 shows that average values of $L_c(\lambda)$ almost similar for both KM4 and ANTARES site. This effect, already discussed above, may be attributed to a different kind of particulate present in the waters of the two sites.

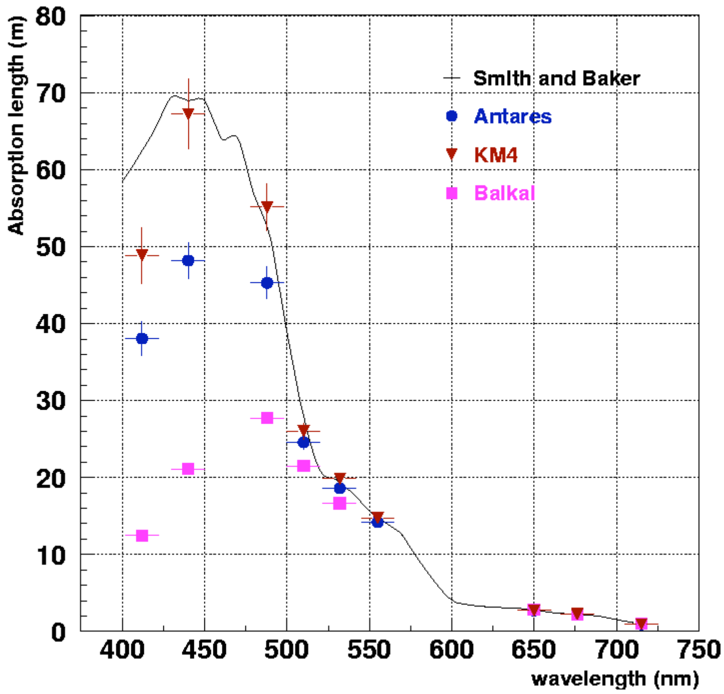

Figure 16 - Comparison between the absorption length average values measured in the sites of Capo Passero KM4 (red triangles), ANTARES (blue circles) and Baikal (purple square). The curve relative to optically pure water is plotted in black [7].

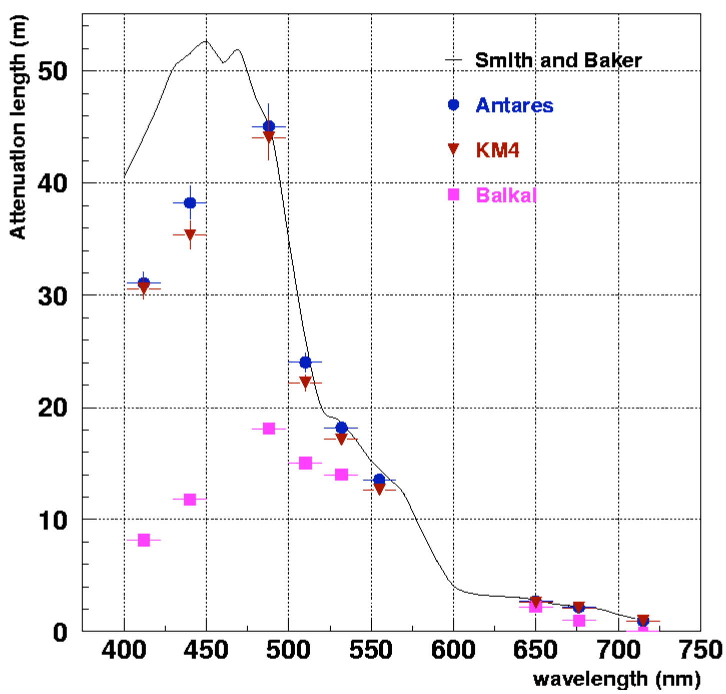

Figure 17 - Comparison between the attenuation length average values measured in the sites of Capo Passero KM4 (red triangles), ANTARES (blue circles) and Baikal (purple square). The curve relative to optically pure water is plotted in black [7].

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