

MEDIUM RESOLUTION IMAGING SPECTROMETER (MERIS) VALIDATION : EARLY RESULTS AT THE BOUSSOLE SITE (MEDITERRANEAN SEA)

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ABSTRACT

The early results of the BOUSSOLE project, which is part of the overall MERIS calibration/validation programme, are presented in this extended abstract ("BOUSSOLE" is a French acronym; in English it basically means "A buoy for the collection of a long-term time-series of optical data").

1. GENERAL OBJECTIVES

A prerequisite to building long-term (over decades) archives of ocean colour, in response to the need for assessing the response of the oceanic biota to climate changes, is to accurately calibrate the top-of-atmosphere satellite observations, then to validate the surface geophysical parameters derived from these observations, and to develop and maintain this capability over long periods of time. Ensuring coherence between these geophysical products, as derived from different sensors, is also an important aspect to consider.

When ocean colour observations from different sensors are considered in view of data merging, their cross-calibration and validation might be facilitated if they could be "anchored" on continuous long-term *in situ* stations [1]. Deploying and maintaining moorings that operate in a continuous way is, however, a difficult program.

In response to these concerns, we have proposed to carry out match-up analyses and vicarious calibration experiments, based on a data set to be built from a permanent marine optical buoy. This new type of marine optical buoy has been specifically designed for the acquisition of radiometric quantities, and has been already deployed in the Mediterranean sea between the French Riviera and Corsica in July 2000 for a 3-month qualification deployment. Another deployment was carried out in May 2002, where a fully operational system was deployed. An unfortunate dysfunction of the main buoyancy package led to the loss of the system. A new deployment of a revised version of the buoy is planned for the spring of 2003.

The vicarious calibration experiments should allow the top-of-atmosphere total radiance to be simulated and compared to the MERIS Top-of-the-atmosphere measurements. By this way, the need for a change of the pre-flight calibration coefficients might be evaluated, and its amount quantified. From the data set we will build, match-up analyses shall be also possible for chlorophyll concentration and water-leaving radiances, as well as algorithm evaluation (atmospheric correction and pigment retrieval). Because of a certain commonality in the band sets of the new-generation ocean colour sensors, the data acquired with the buoy might be used for several of the ocean colour sensors presently in orbit, and then contribute to the international effort of cross-calibrating them and of cross-validating their products, which are amongst the basic goals of the SIMBIOS project [2].

In parallel to these calibration/validation objectives, we will assemble a data set that will be used for more fundamental studies in marine optics and bio-optics. Amongst the questions and topics that we will address are : diurnal cycles of optical properties, response to abrupt environmental changes (*e.g.*, storm, red rains), relationships between chlorophyll and the inherent optical properties, role of a fluctuating interface in establishing the radiative regime, bidirectionality of the radiance field, annual cycles and inter-annual variations of the optical properties, use of these properties as indicators of other, biogeochemical properties, interpretation of the natural fluorescence signal.

2. VICARIOUS CALIBRATION FOR OCEAN COLOUR SENSORS

Vicarious calibration consists in computing the top-of-the-atmosphere total signal that the sensor should measure and to compare it to the signal actually measured. High-accuracy *in situ* data are necessary for the contributions of both the ocean and the atmosphere to the total signal; they are used as inputs and boundary conditions of radiative transfer computations. Section 6 and the following briefly present the data we collect in this context.

The first demonstration of the necessity of vicarious calibration of ocean colour sensors was brought by the CZCS mission. On one hand, this instrument (1979-1986) was not equipped with the necessary onboard devices for the monitoring of the long-term degradation of the instrument response sensitivity (internal lamps suffered a rapid degradation), and, on the other hand, the mission did not include an extensive vicarious calibration programme. At the end, the calibration of the CZCS was never based on firm grounds and has never been sufficiently confirmed for this data set to be fully usable.

The converse situation can be illustrated by the SeaWiFS mission. On the one hand the instrument is equipped with diffusers that allow to track the stability of the instrument (moon + sun), and, on the other hand, an extensive vicarious calibration programme has been set up prior to launching. This programme is essentially based on the deployment of a permanent marine optical buoy (the “MOBY” programme [3]), located in Case 1 waters near Hawaii. In parallel to this central and key element, extensive campaigns are conducted around the World ocean, in order to collect radiometric measurements and ancillary data in a variety of environments; these data are used to permanently evaluate the quality of the level-2 products and improving, when possible, the algorithms.

Such programmes allow the maintenance of the calibration of ocean colour sensors at the desired level over the full course of the missions, which are generally of about 5 years. The difficulty is simply due to inescapable physical considerations : the goal of modern ocean colour sensors is to provide the water-leaving radiance in the blue with a 5% accuracy over oligotrophic, chlorophyll-poor, waters [4, 5, 6]. Because this marine signal only represents about 10% maximum of the total radiance at the top of the atmosphere level (i.e., the radiance directly measured by the sensor), reaching this goal would mean that instruments are calibrated to better than 0.5%, say 1%.

3. WHY WE SELECTED THE SOLUTION OF A PERMANENT MOORING

Maintaining a permanent optical mooring should be a cost-effective and pertinent solution to collect a significant number of data that will be of help in the vicarious calibration and validation processes. Another main option consists in deploying oceanographic ships in various part of the World ocean. It occurs frequently, however, that a very few points are at the end available from such campaigns. This is simply due to the number of conditions that must be simultaneously fulfilled for a measurement to be usable for cal/val of ocean colour sensors (clear sky, low wind speed, acquisition within a maximum of 2 hours from the satellite pass, nominal operation of the instruments etc..).

It has been estimated that the permanent system to be deployed within the frame of the BOUSSOLE project should be able to generate about 20 to 25 matchup points if deployed during 6 months (a reasonable goal for 2003), and up to 50 points if permanently operating. This would, however, probably necessitate 2 systems in a rotation scenario. These numbers are based on a total number of MERIS passes over our site equal to about 200 per year, and to a rejection rate of $\frac{3}{4}$ of the data (i.e., data not usable for match ups because of clouds, glint etc..).

A permanent mooring is adapted to maintaining over years a consistent time series of *in situ* measurements. Ensuring consistency between different teams, equipment and protocols from different cruises (different ships) is on the contrary more uncertain, and inevitably adds some uncertainty in the accuracy of the overall process. A permanent station is as well an ideal frame for developing and testing new instrumentation and new algorithms, and therefore to permanently improve the quality and the variety of products that can be derived from the ocean colour observations at the top-of-the-atmosphere level. It is as well a unique opportunity to establish the cross calibration between different sensors by anchoring them to the same *in situ* time series.

4. THE SELECTED SITE

The mooring is deployed by 43°22'N / 7°54'E, which is located in the Ligurian sea (Western Mediterranean sea, see Fig. 1; depth is 2350 m). This site has been originally selected in the frame of the JGOFS-France activities, because currents are extremely low (the site is nearly at the centre of the cyclonic circulation of the Ligurian sea). Oligotrophic conditions prevail at this site in summer and at certain periods in winter, while a reasonable range of Chl is attainable thanks to (1) a spring bloom with concentrations up to 2 mg m⁻³, (2) a secondary and less intense bloom in fall, and (3) local enhancements in winter when sunny weather temporarily stabilises the nutrient-rich waters.

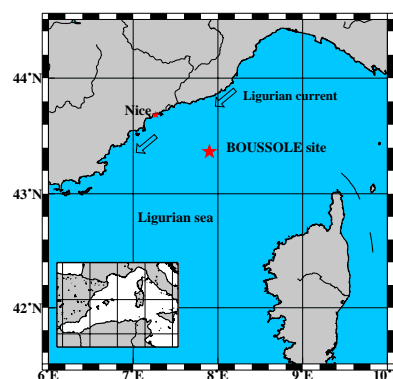


Fig. 1 : map of the BOUSSOLE site location

5. THE BUOY

5.1 Design

The two following paragraphs summarise the rationale for the design of a totally new type of optical buoy, and describe the main characteristics of the system.

Platforms developed for oceanographic purposes are rarely adapted to the deployment of radiometers at sea. Indeed, recording the light field within the ocean interior is difficult because the instruments themselves and, more dramatically, the platform onto which they are installed, inevitably introduce perturbations (shadowing in particular). Other difficulties originate from the need to keep the instruments as much horizontal as possible, either because a plane irradiance is aimed at (cosine sensor), or if a given direction (generally nadir) is aimed at. The actual measurement depth is also difficult to accurately assess, because rapid vertical displacements of the instruments sometimes occur, which prevent any precise estimation of pressure, thence of depth. Considering the above observations (among others), we have developed a new type of platform, dedicated to radiometry measurements, able to minimise shadowing effects, to minimise perturbation of the sub-marine light field, and to warrant the stability of the instruments.

The principle is that of a “reversed pendulum”, with Archimedes thrust replacing gravity. A large sphere (\varnothing 1.8 m) is stabilised at a 18 metres depth out of the effect of most swells (a cable goes down to the sea floor), and creates the main buoyancy of the system. Above the sphere, a rigid, tubular, structure is fixed, which hosts the instrumentation onto horizontal arms (at 5 and 9 metres). An \sim 3 tons thrust ensures the stability of the system, which is subject to very limited forces from the so-called “transparent-to-swell” superstructure. With such a design, there is no large body at the surface generating shade and the stability of the instruments is warranted even for quite large swells.

5.2 The different steps of the construction and testing

A reduced scale model (scale 1/10; see Fig. 2) has been developed in order to verify the theoretical calculations initially performed, and it has been tested in an engineering pool, by applying to it several types of swells and currents (mono chromatic or random swells, up to 5 meters real scale). Results of these tests have fully confirmed the theoretical predictions, in terms of horizontal and vertical displacements (the latter are extremely low), as well as in terms of angular deviations from the vertical. For instance, the mean tilt of the buoy is $\sim 4^\circ$ (with $\pm \sim 4^\circ$ of pitching), for a 4.6-meter swell of period 5.2 seconds (*i.e.*, at the limit before breaking occurs). These tests have also confirmed that no “hidden defect”, hardly discernible via calculations only, was compromising the feasibility of the system. They also shown a significant sensitivity to currents, which are however extremely low on the deployment site. The tests were fully conclusive and led to the construction of the first “beta” version of the buoy, in aluminium.

The full scale “beta version” was built in spring 2000 (see Fig. 2). The material was aluminium for minimising weight. It is made of two parts, the lower one which is from -20 metres to -9 metres below the surface and consists of the sphere and a simple tubular structure, and the upper one which goes from -9 metres below the surface to $+4.5$ metres above the surface, and which hosts the instrumentation. The full-scale beta version has been deployed on site during 3 months (20th of July to the 20th of October, 2000), which allowed to encounter a variety of meteorological situations. The buoy was equipped with two inclinometers, a pressure sensor, an ARGOS beacon and a flashlight. The goal of this deployment was to qualify the new concept of buoy as well as to identify possible problems necessitating modifications. The buoy once installed is shown in Fig. 2.

The results of the qualification deployment confirmed the theoretical prediction and the tests with the reduced-scale model, yet they also showed a certain lack of righting torque, with consequences on the behaviour of the buoy when the swell becomes greater than about 2 metres. Although not dramatic, this behaviour was not totally satisfactory, so that it was decided to introduce slight modifications in the design and construction of the buoy in order to improve the percentage of time for which the requirements in terms of inclination is satisfied.

One modification has been introduced in the design of the buoy, by installing the sphere at 17 metres instead of 18 metres. By this way, the distance from the centre of the sphere to the fixation of the buoy to the mooring cable is one metre greater (the righting torque is therefore much larger). Another modification has been introduced in the materials used to build the upper part of the buoy (the one equipped with arms and the instrumentation), from aluminium to carbon composite. A specific study has been conducted to check that this composite material was adapted to our problem, which is definitely the case. This study was also used for dimensioning the material used for construction.

The impacts of these 2 changes on the upper part of the system are : rigidity is improved, weight is diminished by the 2/3, corrosion is eliminated for the carbon part, the drag coefficient is reduced by the use of tubes with a lower diameter, and the margin between the elastic limit of the material and the forces applied to it by breaking waves is larger than it was. At the end, a net gain of 60% in the righting torque has been obtained for the full buoy.

The modified version of the buoy has been deployed on site with all its instrumentation the 16th of May, 2002. Some images of the May 2002 deployment are shown in Fig. 2. Soon after this deployment, a “non nominal” behaviour of the buoy was identified. The buoy was lost (it sunk) around the 10 of June because the main buoyancy package failed.

A new system is in preparation, which will take benefit from the results of two parallel engineering studies that have been ordered by ESA to the MARINTEK company (Norway) and by CNES to IFREMER (France), in order to gain some external expertise on the BOUSSOLE buoy. The results of these two studies mostly confirm the theoretical predictions that were previously carried out, as well as the interpretation of the tests on the reduced-scale model. Advice has been provided about the different possibilities to construct the buoy so that it is safer than the previous version. The new system will be deployed in Spring 2003.

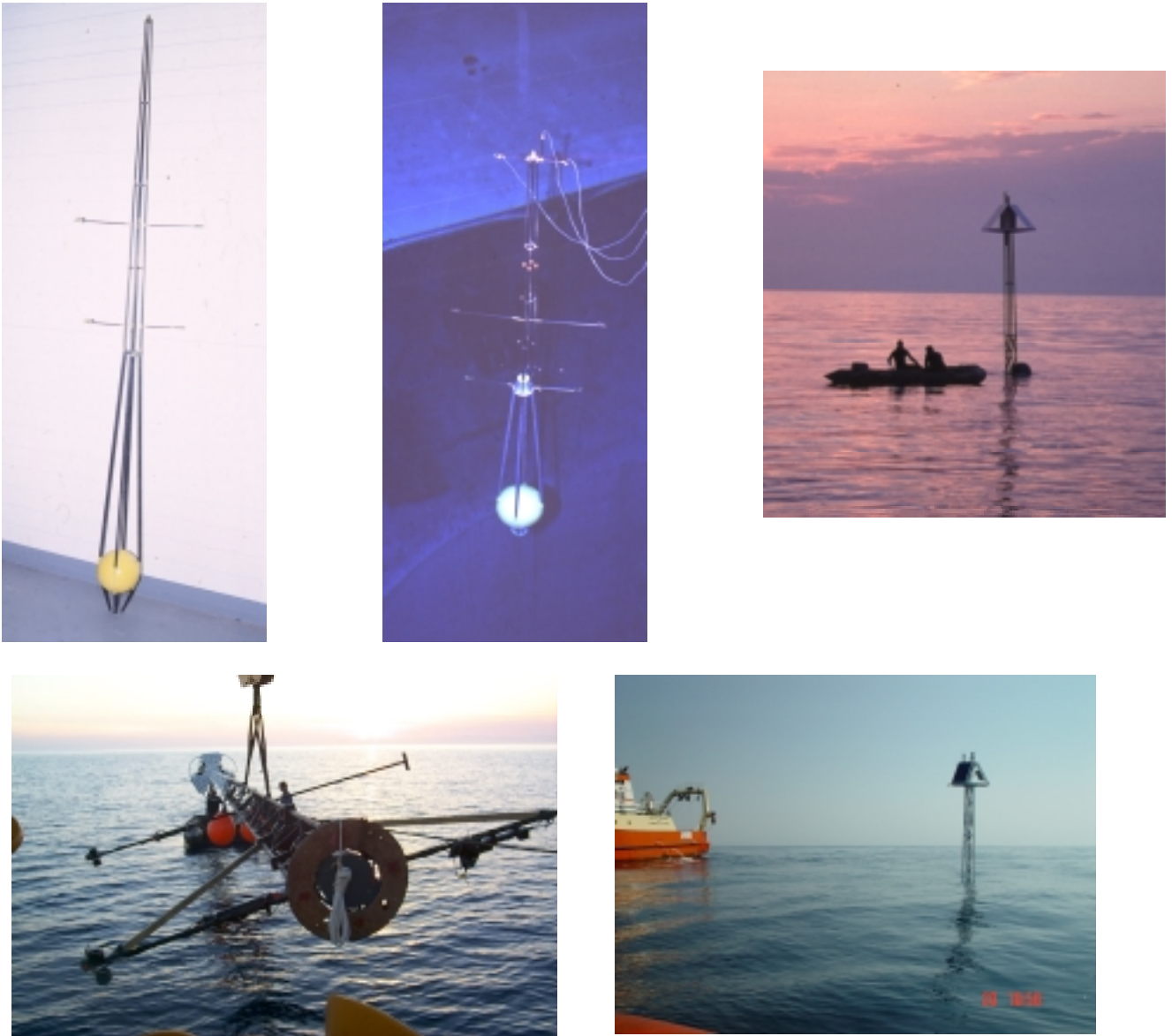


Fig. 2 : From left to right on the upper part : the reduced-scale (1/10) model before and after its installation in the engineering pool, where it is equipped with the sensors needed to record its behaviour when subject to various swells and currents. The “beta” version (aluminium) after its deployment in July 2000 (3-month qualification deployment needed to check the feasibility of the system). From left to right on the lower part : the instrumented part of the buoy, when deployed at sea (May 16, 2002) in order to connect it to the lower part of the buoy, previously installed and adjusted to the correct depth. The operational buoy as it appeared a few days after its deployment (May 20, 2002).

6. THE INSTRUMENTATION ON THE BUOY

The instrument suite on the buoy includes :

- Satlantic 200 series radiometers, measuring the downwelling irradiance impinging onto the ocean surface (E_s , at +4.5 meters above surface), and the downwelling and upwelling irradiances (E_d and E_u) and the upwelling radiance at nadir (L_u) at 2 depths, namely 5 and 9 meters. The 2-axis tilt, the compass (*i.e.*, orientation of the buoy arms with respect to the sun) and the pressure are also recorded.
- Chelsea MiniTracka Fluorometers, at the 2 same depths, for a proxy to Chl.
- Wetlabs WetStar Transmissometer, at the deepest sampling depth (9 m), for a proxy to the particle load.
- Seabird SBE 37SI CTD sensor, at 9 meters, mainly for pressure, temperature and salinity.
- Hobilabs HydrosCat-2 Backscattering meter for a proxy to b_p at 2 wavelengths (443 and 560 nm), at 9 meters.

From these measurements, various AOPs or IOPs might be derived, as the water-leaving radiance, L_w , the diffuse attenuation coefficients for upwelling and downwelling irradiance, K_u and K_d , the attenuation coefficient for upwelling radiance, K_L , the diffuse reflectance just below the sea surface, R , the “nadir Q” factor, E_u/L_u , the attenuation and backscattering coefficients, c and b_p . The absorption coefficient, a , will be tentatively derived through inversion of the AOPs (using for instance K_d and R ; *e.g.*, see [7, 8, 9, 10]).

All measurements are simultaneously collected and centralised by a unique (acquisition / storage / communication) system, that merge the data and send them to the visiting ship via a RF link. Part of the data is transmitted in real time by an ARGOS link, mostly for checking that everything’s working well and that batteries remain charged.

7. THE COASTAL SITE FOR ATMOSPHERIC MEASUREMENTS

Since July 3rd 2002, a coastal site (“Cap Ferrat”, in front of the laboratory, by 43°41’N, 7°19’E) is equipped with an automatic sun photometer station, introduced within the AERONET ([11] <http://aeronet.gsfc.nasa.gov>). This equipment provides a continuous record of the sky radiances (principal plane and almucantar) and of the attenuation of the direct solar beam, from which aerosol types and aerosol optical thickness will be retrieved. The annual calibration are managed by the AERONET [12], as well as the inversion of the sun photometer measurements in order to get the aerosol optical thickness. The procedures are described for instance in [13, 14, 15, 16, 17, 18].

8. MONTHLY ADDITIONAL MEASUREMENTS AND BOUSSOLE SITE CHARACTERISATION

Eighteen 3-day monthly campaigns have been organised on the BOUSSOLE site since July 2001. These campaigns have been used to set up most of the activities that will be necessary during future monthly servicing to the buoy, to collect the discrete data complementary to the data collected in continuous mode from the buoy, and to progressively improve the knowledge of the site properties (“site characterisation”). These activities have included :

- Verification of the mooring line by divers (when it was still on site in 2000-2001; only the buoy has been removed).
- Deployment of several optical profilers.
- Water sampling for subsequent HPLC determination of the phytoplankton pigments.
- Conductivity-Temperature-Depth (CTD) profiles and inherent optical properties (IOP) profiles.
- Inter-comparison between above-water determination of the water-leaving radiance (SIMBADA instrument; see at http://www-loa.univ-lille1.fr/recherche/ocean_color/src) and below-water determination of the same quantity.
- Determination of the aerosol optical thickness.
- Characterisation of the spatial heterogeneity of the site, by following a grid pattern with a fluorometer, the pattern being then calibrated in terms of chlorophyll concentration (discrete samples are taken along the grid).

9. CALIBRATION AND CHARACTERISATION OF THE RADIOMETERS, BIOFOULING

The strategy for the calibration of the buoy’ radiometers is to replace each month one set of instruments by another, cleaned and calibrated, set of instruments. The recovered set of radiometers is brought back to the laboratory for relative calibration (use of the SQM-II ultra stable lamp) and cleaning. One month later, the exchange is again performed and so on. We first have set up the installation of the SQM-II and have worked towards establishing the routine operations that are necessary each months on each set of radiometers (the so-called “SQM sessions”).

Experiments [19] have been performed in 2001-2002 at the Ispra Joint Research Centre (JRC, Guiseppe Zibordi’s team), Scripps Institution of Oceanography (San Diego, Jim Mueller’s team) and Satlantic company (Halifax, Canada), in order to fully revise the values of the immersion coefficients and cosine responses of Satlantic 200 series radiometers (*i.e.*, the ones used by BOUSSOLE). These experiments (referred to as the Sirrex-8 experiment) were set up after inconsistencies in some measurements increasingly put forward the fact that the immersion coefficients initially determined were probably no longer valid. The output of these experiments have been released in 2002, and the new values coming from these experiments will be considered.

A specific apparatus is being set up in our laboratory, which will take benefit from the developments carried out at the JRC during the above mentioned Sirrex-8 exercise. The system is based upon a small water tank at the base of which is installed the radiometer to be characterised. This system has been cross-checked against more “classical” experimental set ups previously used for the determination of the immersion coefficient. This apparatus will actually be used as well to estimate the contribution of bio-fouling, if any, through the changes in the immersion coefficients. Concerning bio-fouling on the radiometers, another part of our strategy is their monthly replacement by clean and calibrated radiometers (note that the bio-optical conditions at the BOUSSOLE site, *i.e.*, oligotrophy to mesotrophy, are in principle favourable to minimise the difficulty).

10. EARLY RESULTS

The early results presented in this section just provides a partial view of what type of data are collected at the BOUSSOLE site. These data are all preliminary data, still necessitating further quality controls and analyses.

10.1 CTD and IOP vertical profiles

CTD profiles (about 60 up to now) are performed at the beginning and end of the optics sessions, and also in between when the sessions last more than about 2 hours. They include the vertical profiles of temperature, salinity, pressure, oxygen and fluorescence. Since June 2002, they include as well the absorption and attenuation coefficients at 9 wavelengths from an AC9 instrument. Other inherent optical properties, namely the backscattering coefficient and the fluorescence of the coloured dissolved organic matter, have been progressively introduced starting in fall 2002.

10.2 Determination of phytoplankton pigments (HPLC)

Before the rosette is brought back on deck, triplicate water samples are taken at 5 and 10 meters for subsequent filtration (GF/F) and freezing (liquid nitrogen). These two operations are performed aboard the ship. When back to the laboratory filters are stored at -80°C before they are analysed. About 250 individual samples have been collected up to now. Determination of the pigments by HPLC follows standard procedures [20], which have been cross-checked against other procedures during an international round robin experiment [21]. Mean surface values are shown on Fig. 3 below.

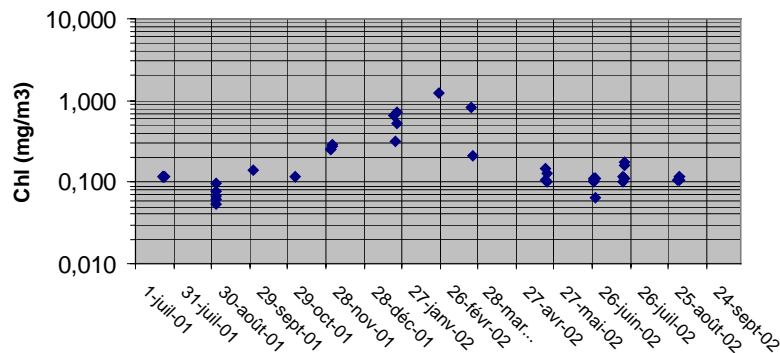


Fig. 3. Total Chl-a concentration in surface waters at the BOUSSOLE site, from July 2001 to September 2002. Each point on this figure represents a mean surface value, which is derived from several samples taken at 5 and 10 meters depth.

10.3 In-water radiometry

Fig. 4 shows the reflectance at 443 and 555 nm, as derived from the vertical profile of the upwelling irradiance extrapolated to null depth, and the above-surface reference value for the downwelling irradiance corrected for the air-sea transmission. This plot also displays the water-leaving radiance, which is the value directly comparable to what is derived from the measurement performed by ocean colour sensors. It is computed from R and by using a modelled value of the Q factor [22]. About 200 optical casts have been performed up to now, and only a selection of these profiles have been used to compute the reflectances and radiances shown in Fig. 4.

As expected in Case 1 waters, the reflectance R is decreasing in the blue (443 nm) with increasing chlorophyll concentration, except between July and the beginning of September in 2001, where the converse holds. At this time of the year, the reflectance in the blue seems therefore lower than what it should be for nominal Case 1 waters. This anomalous situation has been already described for September 1999 in the Mediterranean sea [23]. The minimum in the reflectance at 443 nm is observed in January (the normalised value is about 2%) and the maximum (4 to 5%) in July.

The behaviour of the reflectance in the green is a bit more complex, and two periods of the year again departs from what is expected in Case 1 waters. Between September and November, the chlorophyll concentration increases from about 0.05 to 0.15 mg m⁻³ while R(555) decreases, and between January and March the chlorophyll concentration

decreases a little while $R(555)$ increases. Further analysis is needed to interpret these seasonal patterns, in particular by using the upcoming inherent optical properties determinations.

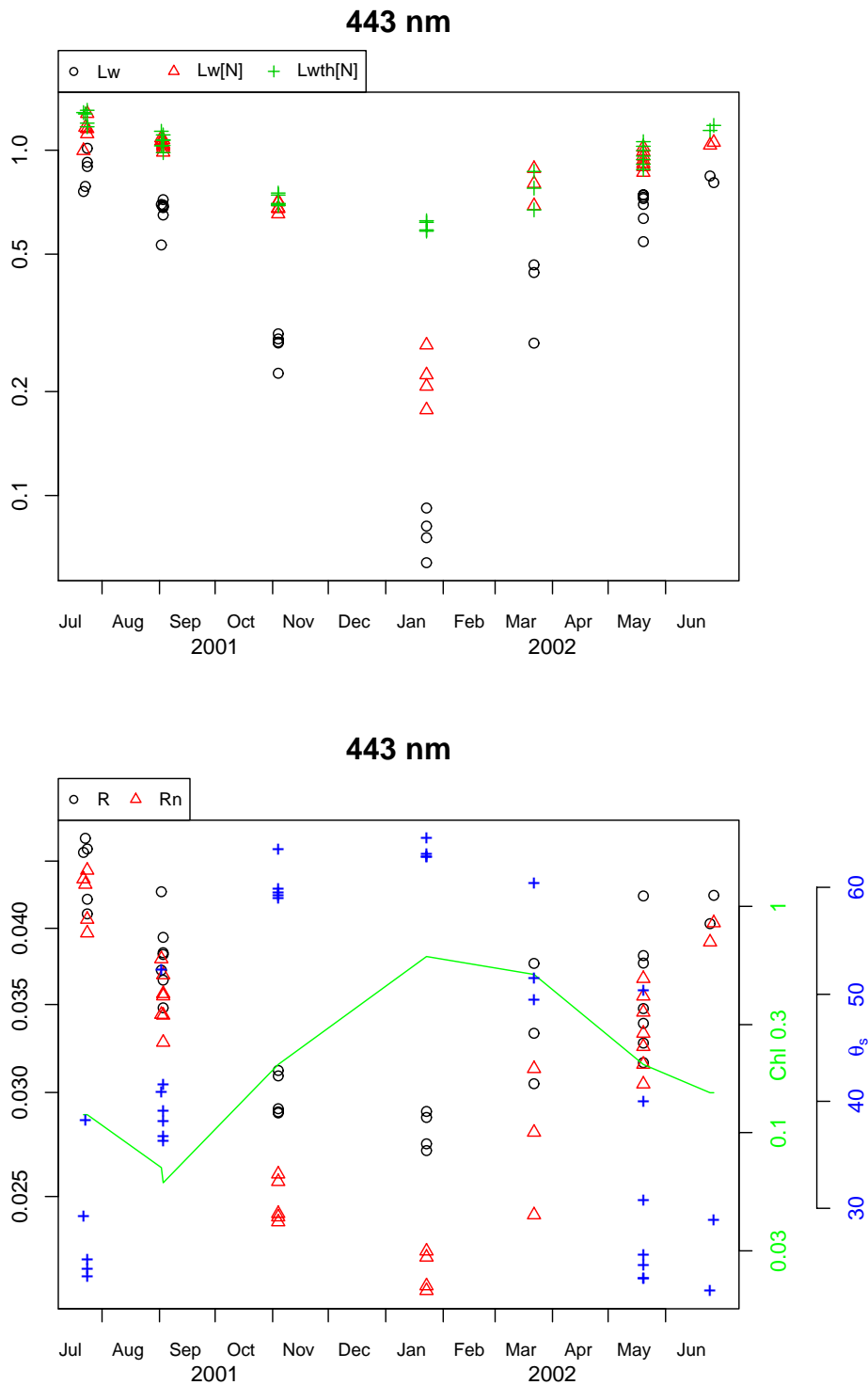


Fig. 4 : **bottom** : time series of the ocean diffuse reflectance at 443 nm, R (open black circles), and of its normalised value R_n (red triangles). The values of the sun zenith angle are also shown (plus signs in blue) as well as the chlorophyll concentration (green curve, scale on the right y-axis). **Top** : values of the water-leaving radiance at the same wavelength (L_w ; open circles) and of its normalised value, as computed through two different procedures (red triangles and plus signs). Units are $\text{mW}/\text{cm}^2/\text{sr}/\text{nm}$. The difference between these 2 estimates (which should be extremely small in good measurement conditions) indicates that the data collected in January 2002 are likely to be of poor quality because of the sky conditions.

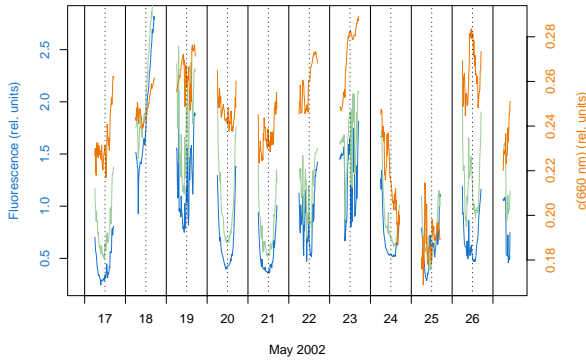


Fig. 6(a). 10-day time series of the beam attenuation coefficient measured at 660 nm on the buoy, at a depth of 9 meters (orange curve). The phytoplankton fluorescence is also displayed, as measured at 4 and 9 meters (blue and green curves, respectively).

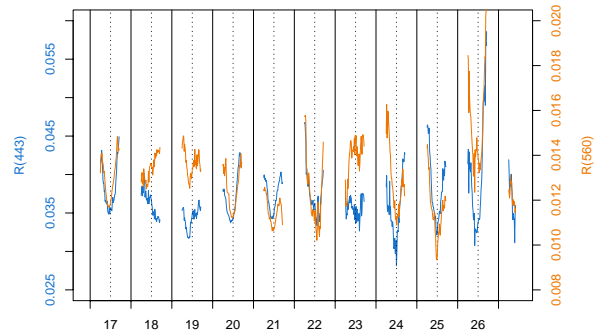


Fig. 6(b). 10-day time series of the diffuse ocean reflectance at 443 nm (blue curve) and 560 nm (orange curve) on the buoy.

10.4 Buoy radiometry and inherent optical properties

Fig. 6 shows a 10-day time series obtained from the buoy, just after its deployment on May 16, 2002, for the water-leaving radiance at nadir (L_w), the diffuse ocean reflectance (R), the attenuation coefficient and the fluorescence.

The 17th of May 2002 was a clear-sky day. The daily course of the reflectance shows accordingly a smooth pattern with a minimum at local solar noon. This pattern is mostly the result of the change in the solar elevation, whereas the inherent optical properties are rather constant throughout the day as indicated by the $c(660)$ coefficient. Other clear-sky conditions occurred the 20th and the 21st of May (*cf.* last panel of Fig. 2); they show similar patterns for the phytoplankton fluorescence, the beam attenuation coefficient and the reflectances.

A very different situation occurs on May 18, with a nearly continuous increase of the phytoplankton fluorescence and of the particle load (as depicted by the proxy $c(660)$), from a few hours after sun rise to sun set. The reflectance accordingly decreases in the blue while it increases in the green, so that the “blue-to-green” ratio goes down from about 1 to 0.8.

These preliminary results, which should be completed by a much longer time-series as soon as the new system is deployed in 2003, already show the potential of the continuous measurements carried out on the buoy.

10.5 Match up with MERIS data

An example of a match up with MERIS observations is displayed in Fig. 7. The agreement between the *in situ* determination of the reflectance and its value derived from the MERIS top-of-the-atmosphere observations is excellent in the blue and green parts of the spectrum, while it degrades a little in the red. Several tens of such comparisons will be needed (in parallel to the vicarious calibration which is not discussed in this paper) in order to re-evaluate on firm grounds the MERIS calibration as well as to introduce possible algorithms modifications.

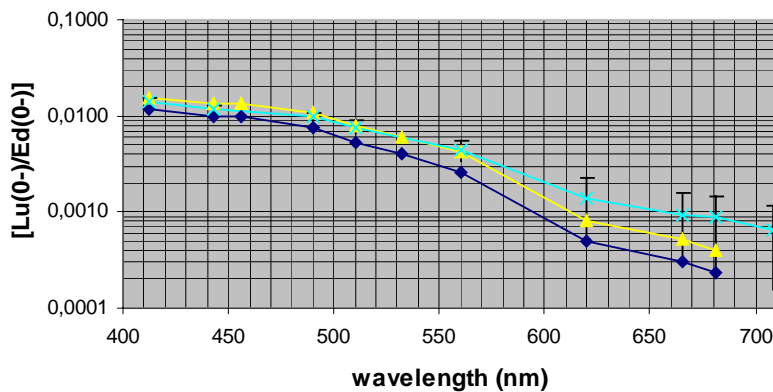


Fig. 7 : reflectance spectra as derived from MERIS (light blue curve; extracted from an image taken above the BOUSSOLE site on the 5th of October, 2002), and as derived from *in situ* measurements (dark blue and yellow curves, collected at two different times of the day) The vertical bars are $\pm 1\sigma$, as computed for a 5 by 5 pixel box centred onto the pixel closest to the *in situ* measurement site. The atmospheric correction procedure used to derive the marine radiance spectrum from the MERIS observations is described in [6]. It is the procedure implemented in the MERIS operational ground segment.

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