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Analysis of simultaneous chlorophyll measurements by lidar fluorosensor, MODIS and SeaWiFS

R. BARBINI†, F. COLAO†, L. DE DOMINICIS†, R. FANTONI†, L. FIORANI*†, A. PALUCCI† and E. S. ARTAMONOV‡

†ENEA, FIS-LAS, Via Fermi 45, 00044 Frascati, Italy
‡ENEA guest (SB RAS, IAO, Akademicheskii Avenue 1, Tomsk 634055, Russia)

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Abstract. The ENEA (Italian Agency for New Technologies, Energy and the Environment) lidar fluorosensor (ELF), aboard the research vessel *Italica*, measured continuously surface chlorophyll-a concentrations during the Italy–New Zealand and New Zealand–Italy transects (13 November–18 December 2001 and 28 February–1 April 2002, respectively). The ELF measurements were compared with the data collected by the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the Moderate Resolution Imaging Spectroradiometer (MODIS). This study pointed out advantages, disadvantages and possible synergies of lidar fluorosensor and spaceborne radiometers. In particular, the SeaWiFS and MODIS bio-optical algorithms have been calibrated with the ELF measurements. The differences between the performances of the two spaceborne radiometers are also briefly discussed.

1. Introduction

Ocean colour satellites (Hovis 1980, Hooker *et al.* 1992, Esaias *et al.* 1998, Cracknell *et al.* 2001) have changed the way we can observe the Earth: planetary maps of the surface chlorophyll-a concentration (Kirk 1994, Falkowski and Raven 1997), and hence of the phytoplankton primary productivity (Behrenfeld and Falkowski 1997, Joint and Groom 2000), can be retrieved in few days. Nevertheless, these results are the product of complex calculations: atmospheric corrections (Gordon and Wang 1994, Fiorani *et al.* 1998) and bio-optical algorithms (Aiken *et al.* 1995, O'Reilly *et al.* 1998) have to be applied on the raw water-leaving radiances measured by the spaceborne radiometers. For this reason the remote sensed images have to be calibrated and validated by *in situ* instruments (Hooker *et al.* 1994, 1999, 2000, O'Reilly *et al.* 1998, 2000, Hooker and Lazin 2000, McClain *et al.* 2000, Eplee *et al.* 2001, Firestone and Hooker 2001) usually operated from marine buoys, fixed stations and research vessels (RVs).

In this framework, it has been decided to measure the surface chlorophyll-a concentration with the ENEA (Italian Agency for New Technologies, Energy and

*Corresponding author; e-mail: fiorani@frascati.enea.it

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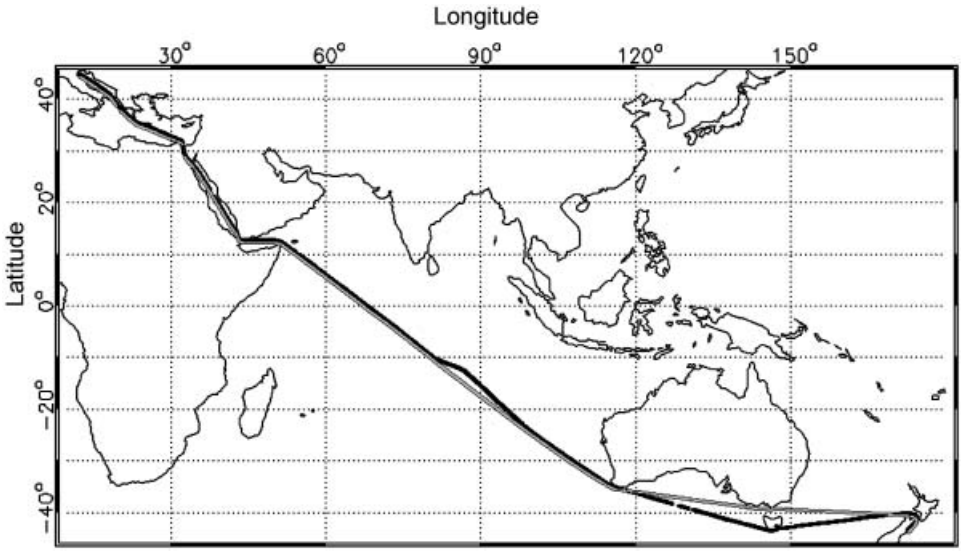

Figure 1. The study area. Thick black line: Italy–New Zealand transect (13 November–18 December 2001). Thick grey line: New Zealand–Italy transect (28 February–1 April 2002). The two departures from the shortest track in the Italy–New Zealand transect (longitudes around 85° and 145°) are due to a deviation to avoid a hurricane and to a stop in Hobart Harbour to unload materials for the French researchers.

the Environment) lidar fluorosensor (ELF) (Barbini *et al.* 1999, 2001a,b, 2003) aboard the RV *Italica*, covering the Italy–New Zealand and New Zealand–Italy transects in its navigation to and from Antarctica (figure 1) (Colao *et al.* 2002). This study is part of the MIPOT (Mediterranean Sea, Indian and Pacific Oceans Transect) oceanographic campaign. MIPOT provided *in situ* data for 69 days (13 November–18 December 2001, 28 February–1 April 2002) in the less studied marine zones, e.g. the Red Sea and the Indian Ocean are not included in the SeaBAM dataset used for the SeaWiFS calibration (O'Reilly *et al.* 1998). ELF operated continuously, except for rare and short maintenance stops.

In some sense, passive (radiometers) (Elachi 1987) and active (lidar) (Measures 1992) remote sensing are complementary; on one hand, passive remote sensing provides global coverage but requires calibrations and validations, on the other, active remote sensing is accurate but can sound a limited region. In order to merge the advantages of both techniques, the lidar data can be used for the validation of the radiometers and for the calibration of the bio-optical algorithms, allowing one to better estimate primary productivity, and hence to improve the understanding of the ocean role in the global carbon cycle and, as a consequence, in the planetary climate equilibrium (Falkowski *et al.* 2000).

In this paper, ELF, the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) (Hooker *et al.* 1992) and the Moderate Resolution Imaging Spectroradiometer (MODIS) (Esaias *et al.* 1998) are briefly described and their chlorophyll-a data are compared. Eventually, the ELF measurements are used in a new calibration of the bio-optical algorithms.

2. Instruments and methods

2.1. *ELF*

The experimental set up of ELF, the ancillary instruments assisting its operation and the algorithm employed for the data analysis have been already published elsewhere (Barbini *et al.* 1999, 2001a,b, 2003), hence here we will only recall its main features. ELF relies on the observation of the Raman backscattering of water (at 404 nm) and the fluorescence of chlorophyll-a (at 680 nm), both induced by a laser pulse (at 355 nm): the absolute concentration of that pigment is directly proportional to the fluorescence-to-Raman ratio (also known as concentration released in Raman units).

Chlorophyll-a fluorescence variations related to changes in the downwelling light field have been observed. They have been corrected according to the algorithm described by Hoge *et al.* (1998) relying on the measurements of photosynthetically available radiation carried out by our solar radiance detector.

The Raman units are converted into $\mathrm{mg\,m^{-3}}$, i.e. the absolute concentration is retrieved from the fluorescence-to-Raman ratio, by calibration against conventional analysis on the same water (V. Saggiomo and co-workers, Zoological Station, Naples, unpublished data, 2002). During the cruise described in this paper, 332 conventional analyses were performed according to the spectrofluorometric technique described by Lorenzen and Jeffrey (1980). The correlation coefficient between fluorescence-to-Raman ratio and absolute concentration was 0.82 (Colao *et al.* 2002).

2.2. *SeaWiFS and MODIS*

Following the wide success of the Coastal Zone Colour Scanner (CZCS) (Hovis 1980), operated on the Nimbus-7 satellite from 1978 to 1986, two new radiometers, SeaWiFS (Hooker *et al.* 1992) and MODIS (Esaias *et al.* 1998), were launched in 1 August 1997 and 18 December 1999, respectively. The first, aboard OrbView-2, is a joint venture of Orbital Sciences Corporation and the National Aeronautics and Space Administration (NASA). The second, integrated on Terra, is part of the NASA's Earth Observing System (EOS), a programme including six spacecrafts: Aqua, Aura, ICESat, Landsat 7, SORCE and Terra (a second MODIS was launched on Aqua on 4 May 2002, after the cruise described in this paper).

SeaWiFS and MODIS, as well as all the main ocean colour sensors, have been reviewed recently by Cracknell *et al.* (2001). Let us remind here only that SeaWiFS and MODIS have been designed for the observation of phytoplankton biochemistry: in particular, they are expected to provide surface chlorophyll-a concentration over the range 0.05–50 $\mathrm{mg\,m^{-3}}$. The main characteristics of SeaWiFS and MODIS are summarized in table 1.

3. Comparison among ELF, SeaWiFS and MODIS data

The temporal and spatial resolutions of ELF, SeaWiFS and MODIS are very different: while a laser pulse is emitted every 0.1 s and the beam footprint on the water surface has a diameter of about 10 cm, a satellite swath is acquired in some minutes and a radiometer pixel sizes around 1 km. The temporal and spatial resolution of the spaceborne sensors degrades further passing from raw to processed imagery. Conversely, as far as depth is concerned, lidar and radiometers probe a similar layer of the order of magnitude of 10 m (depending on water turbidity).

Table 1. Specifications of SeaWiFS and MODIS.

	SeaWiFS	MODIS
Scan width (°)	±58.3*, ±45.0†	±55°
Scan coverage (km)	2800*, 1500†	2330
Nadir resolution (km)	1.13*, 4.5†	0.25‡, 0.5§, 1¶
Number of bands	8	36
Wavelength coverage (nm)	412–865	405–14 385
Tilt (°)	20, 0, +20	no
Digitization	10 bits	12 bits
Acquisition start	4 September 1997	24 February 2000

*Local area coverage, †global area coverage, ‡bands 1–2, §bands 3–7, ¶bands 8–36.

In this study, level 3 (L3) daily Standard Mapped Image (SMI) products were used both for SeaWiFS and MODIS. Moreover, only non-questionable pixels were retained (quality flag = 0). L3 daily SMI products were chosen for the following reasons:

- L3 is more accurate than level 2 (L2): on one hand, each L3 measurement is the result of the spatial and temporal average of some L2 data (Campbell *et al.* 1995), on the other hand, problems missed during the review of L2 products can be identified in the L3 fields (McClain *et al.* 1992); the final accuracy of the chlorophyll-a retrieval by SeaWiFS is of the order of 50% (O'Reilly *et al.* 2000).
- Daily files have the finer temporal resolution available for L3 (i.e. 1 day).
- SMI products of SeaWiFS and MODIS are readily comparable (one SeaWiFS pixel contains exactly four MODIS pixels).

To sum up, the choice of L3 daily SMI products led to a temporal resolution of 1 day and a geometrical resolutions of $5'16'' \times 5'16''$ (corresponding to a spatial resolution of about $9\,\mathrm{km} \times 9\,\mathrm{km}$) and $2'38'' \times 2'38''$ (corresponding to a spatial resolution of about $4.5\,\mathrm{km} \times 4.5\,\mathrm{km}$) for SeaWiFS and MODIS, respectively. As a consequence, some processing was necessary to compare ELF, SeaWiFS and MODIS data. At first, the four MODIS pixels falling in a SeaWiFS pixel were averaged, so that the L3 products of both radiometers had the same temporal and spatial resolution (1 day, about $9\,\mathrm{km} \times 9\,\mathrm{km}$, respectively)—from now on, this average ($5'16'' \times 5'16''$) will be simply called 'MODIS pixel', even if it is not the original MODIS pixel ($2'38'' \times 2'38''$). Secondly, all the ELF measurements falling in a SeaWiFS pixel were averaged, thus representing a nearly straight track (length $\sim 10\,\mathrm{km}$, width $\sim 0.1\,\mathrm{m}$) acquired in about 20 min—in the following, we will call this track 'ELF granule'. Eventually, the measurements carried out by lidar and radiometers were considered concurrent if the *in situ* track was acquired on the same day as the remote sensed pixel. Unfortunately, the resolution of radiometers and ELF differs: (1) in time, since the acquisition interval of ELF is short compared with 1 day, (2) in space, because the square of about $9\,\mathrm{km} \times 9\,\mathrm{km}$ observed by radiometers is larger than the track of about $10\,\mathrm{km} \times 0.1\,\mathrm{m}$ sensed by ELF, even if the track is inscribed in the square.

In order to avoid those differences, the ship should have spanned a $9\,\mathrm{km} \times 9\,\mathrm{km}$ area for 1 day. This solution has been discarded—it would have allowed only one concurrent measurement per day and would have led to unaffordable durations of the Italy–New Zealand and New Zealand–Italy transects. That dissimilarity in

temporal and spatial resolutions can be responsible for part of the disagreement between radiometers and ELF.

Actually, the MODIS L3 algorithm provides two empirical values of chlorophyll-a: the standard and the SeaWiFS chlorophyll-a. The first one is derived using the Clark four-band algorithm (Muller-Karger *et al.* 1990), the second one is calculated from MODIS water-leaving radiances using the OC2 SeaWiFS algorithm (O'Reilly *et al.* 1998). This latter algorithm is used for the MODIS data in order to make the comparison between the two radiometers easier, even if SeaWiFS measurement are now processed with OC4 (O'Reilly *et al.* 1998), a slightly modified version of OC2. The concurrent measurements of surface chlorophyll-a concentration carried out by ELF (C_L), SeaWiFS (C_S), MODIS with OC2 (C_{MS}) and MODIS with the standard algorithm (C_M) are shown in figure 2. The equations for C_S, C_{MS} and C_M (in mg m^{-3}) are (O'Reilly *et al.* 1998, Esaias *et al.* 1998)

$$C_S = 10^{\left(a_0 + a_1 R + a_2 R^2 + a_3 R^3\right)} + a_4 \tag{1}$$

where R is the $\log_{10}$ of whichever band ratio, among Rrs(443 nm)/Rrs(555 nm) or Rrs(490 nm)/Rrs(555 nm) or Rrs(510 nm)/Rrs(555 nm), is greatest and Rrs(λ) is the remote sensing reflectance at the wavelength λ,

$$C_{MS} = 10^{\left(b_0 + b_1 R + b_2 R^2 + b_3 R^3\right)} + b_4 \tag{2}$$

where R is the $\log_{10}$ of the band ratio Rrs(488 nm)/Rrs(551 nm),

$$C_M = 10^{\left(c_0 + c_1 X + c_2 X^2 + c_3 X^3\right)} \tag{3}$$

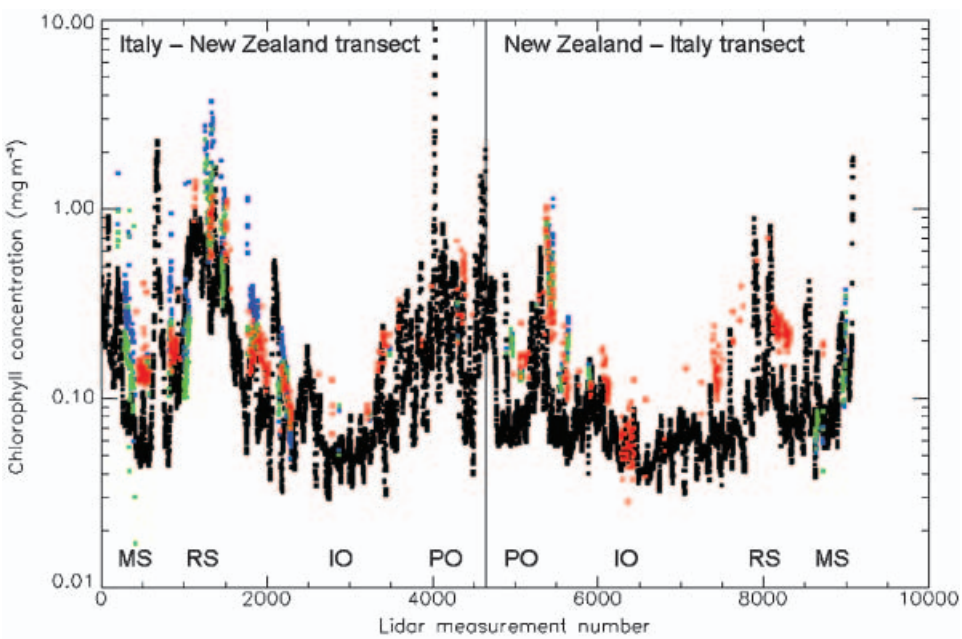

Figure 2. Surface chlorophyll-a concentration measured by ELF (C_L, shown in black), SeaWiFS (C_S, shown in red), MODIS with the OC2 bio-optical algorithm (C_{MS}, shown in green) and MODIS with the standard bio-optical algorithm (C_M, shown in blue). MS, Mediterranean Sea; RS, Red Sea; IO, Indian Ocean; PO, Pacific Ocean.

where

$$X = \frac{L_{wn}(443\,\text{nm}) + L_{wn}(488\,\text{nm}) + L_{wn}(531\,\text{nm})}{L_{wn}(551\,\text{nm})} \tag{4}$$

and Lwn(λ) is the water-leaving radiance at the wavelength λ.

The parameters a_i, b_i ($i=0, 1, 2, 3, 4$) and c_j ($j=0, 1, 2, 3$) are computed from fits of *in situ* chlorophyll-a versus the variables R and X, respectively. Their value is upgraded during the space missions thanks to periodical data reprocessing: for their last update the reader is referred to the web site of SeaWiFS (http://seawifs.gsfc.nasa.gov/) and MODIS (http://modis.gsfc.nasa.gov/).

On many occasions, ELF was able to carry out measurements when SeaWiFS and MODIS were not: during the entire cruise, 9086 ELF granules were collected and only 1318 of them were concurrent to at least one radiometer pixel (784 with a SeaWiFS pixel and 695 with a MODIS pixel). More details on the data acquisition are given in table 2. This partial failure to obtain results was due to the cloud coverage lasting for many days, especially in the Indian Ocean, and to the 10-day shut down of MODIS in March 2002 (Acker 2002).

Figure 2 suggests that ELF performed better in the detection of local anomalies, as one would expect from the higher spatial resolution of the ELF granule with respect to the SeaWiFS and MODIS pixel. C_L is high (about 1 mg m^{-3} or more) in seven cases:

1. in coastal waters of the Mediterranean Sea (lidar measurement number $\sim$100);
2. in the Suez Channel (lidar measurement number $\sim$700);
3. in coastal waters of the Red Sea (lidar measurement number $\sim$1300);
4. in the Hobart Harbour (lidar measurement number $\sim$4000);
5. in coastal waters near New Zealand (lidar measurement number $\sim$4600);
6. in coastal waters of the Red Sea (lidar measurement number $\sim$7900); and
7. in coastal waters of the Mediterranean Sea (lidar measurement number $\sim$9100).

Table 2. Characteristics of the surface chlorophyll-a measurements taken by ELF (C_L), SeaWiFS (C_S), MODIS with the OC2 bio-optical algorithm (C_{MS}) and MODIS with the standard bio-optical algorithm (C_M) during this study.

	Entire cruise	Italy–New Zealand transect	New Zealand–Italy transect
Number of ELF granules	9086	4647	4439
Number of ELF granules concurrent to radiometer pixels	1318	761	557
Number of ELF granules concurrent to SeaWiFS pixels	784	396	388
Number of ELF granules concurrent to MODIS pixels	695	450	245
Average value $\pm$ SD (per cent SD) of C_L/C_S	0.58 $\pm$ 0.29 (50%)	0.61 $\pm$ 0.30 (49%)	0.54 $\pm$ 0.27 (50%)
Average value $\pm$ SD (per cent SD) of C_L/C_{MS}	0.73 $\pm$ 0.55 (75%)	0.77 $\pm$ 0.58 (75%)	0.67 $\pm$ 0.50 (75%)
Average value $\pm$ SD (per cent SD) of C_L/C_M	0.64 $\pm$ 0.59 (92%)	0.63 $\pm$ 0.60 (95%)	0.65 $\pm$ 0.56 (86%)

SD, standard deviation.

Conversely, C_S, C_{MS} and C_M, apart from isolated points, are high in only two cases:

1. in coastal waters of the Red Sea (lidar measurement number $\sim$1300); and
2. in coastal waters of the Pacific Ocean (lidar measurement number $\sim$5400).

Although C_S, C_{MS} and C_M are in general higher than C_L, the agreement among the curves corresponding to all the sensors (figure 2) is rather good. In particular, all the systems find strong concentrations in the Mediterranean Sea, the Red Sea and the Pacific Ocean, especially in the Italy–New Zealand transect. Figure 2 shows also that C_{MS} is usually closer to C_S than C_M. This is not surprising because, while originating from measurements performed by different radiometers, C_{MS} and C_S are computed with nearly the same algorithm.

In order to make the comparison between lidar and radiometers easier, the ratios C_L/C_S, C_L/C_{MS} and C_L/C_M have been plotted in figure 3 and their average values and standard deviations are listed in table 2.

The observation of C_L/C_S, C_L/C_{MS} and C_L/C_M in figure 3 confirms that C_{MS} is usually closer to C_S than C_M. Conversely, if one considers the average values (table 2), C_L/C_M is more similar to C_L/C_S than C_L/C_{MS}. In fact, this is an artefact due to the points at the beginning and at the end of figure 3 where measurements of only one radiometer are present (for the concurrent measurement number $\sim$1–100 C_L/C_{MS} is higher than C_L/C_M and SeaWiFS data lack, for the concurrent measurement number $\sim$1100–1250 C_L/C_S is low and MODIS data lack).

From table 2 we infer that all the values of C_L/C_S, C_L/C_{MS} and C_L/C_M are compatible within the error bars. Moreover, C_L/C_{MS} and C_L/C_M are compatible with unity within the error bars. This is not the case of C_L/C_S: this dissimilar performance is explained also by the higher stability of SeaWiFS with respect to

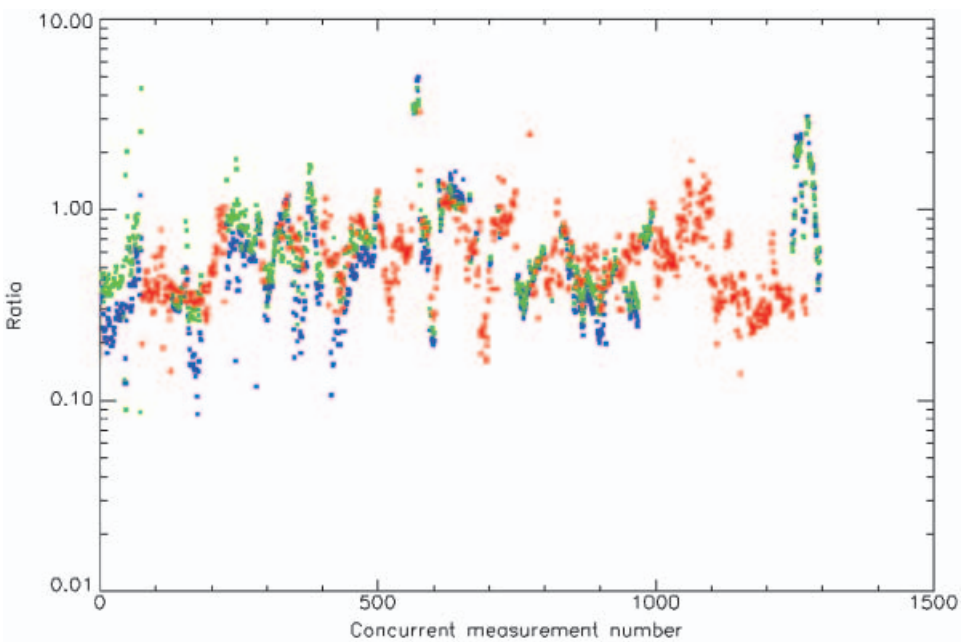

Figure 3. Ratio between the surface chlorophyll-a concentration measured by lidar and radiometers. Red, C_L/C_S; green, C_L/C_{MS}; blue, C_L/C_M.

MODIS, as shown by lower standard deviation (table 2) and less fluctuating behaviour (figure 3). Let us note that the standard deviation of C_L/C_M (Clark algorithm) is higher than the standard deviation of C_L/C_{MS} (OC2 algorithm). This suggests that part of the fluctuation of the MODIS data should be attributed to the Clark algorithm.

In any case, figure 3 and table 2 show that, in general, the radiometers overestimated the surface chlorophyll-a concentration during the Italy–New Zealand and New Zealand–Italy transects. This is exactly the contrary of what was observed in Antarctica (Barbini *et al.* 2001b, 2003), supported by other authors (cited in Barbini *et al.* 2003). In fact, this apparent inconsistency can be explained observing that the concentrations retrieved with concurrent measurements were much higher in Antarctica (up to more than $5\,\mathrm{mg\,m^{-3}}$) than in the Italy–New Zealand and New Zealand–Italy transects (less than $0.75\,\mathrm{mg\,m^{-3}}$). Figure 4, which shows C_L/C_S as a function of C_L, supports this hypothesis: (1) For C_L from 0 to $0.15\,\mathrm{mg\,m^{-3}}$ (621 points), the average value and the standard deviation of C_L/C_S are 0.52 and 0.25, respectively (departure from unity larger than the error bar). (2) For C_L from 0.15 to $0.75\,\mathrm{mg\,m^{-3}}$ (163 points), the average value and the standard deviation of C_L/C_S are 0.79 and 0.33, respectively (departure from unity is not larger than the error bar).

To sum up, the ELF measurements carried out in Antarctica and in the Italy–New Zealand and New Zealand–Italy transects indicate that SeaWiFS and MODIS underestimate high concentrations and overestimate low concentrations. A way to circumvent this problem is to calibrate the SeaWiFS and MODIS bio-optical algorithms with the ELF data.

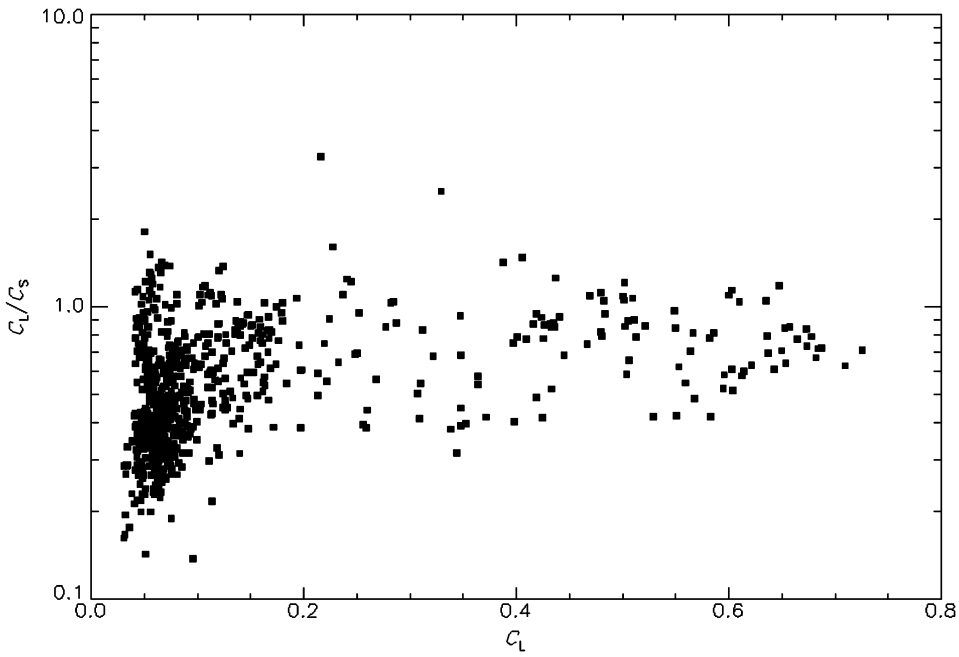

Figure 4. Ratio between the surface chlorophyll-a concentration measured by ELF and SeaWiFS (with the standard bio-optical algorithm) versus the surface chlorophyll-a concentration measured by ELF.

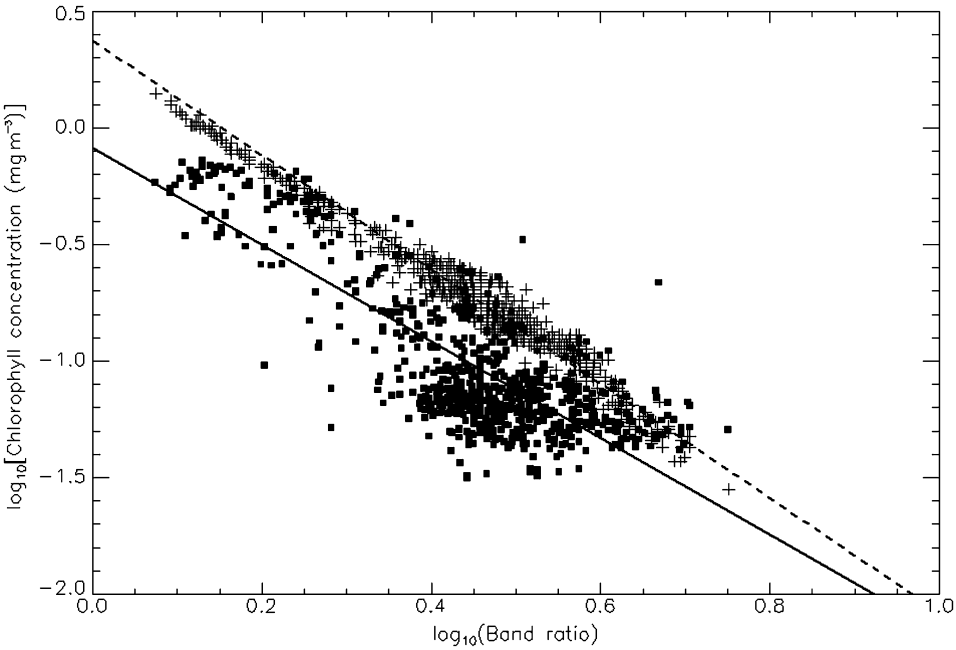

Figure 5. ELF (filled squares) and standard SeaWiFS (plus sign) surface chlorophyll-a concentration versus the SeaWiFS band ratio. The continuous and dashed lines correspond to ELF-calibrated OC1 and standard OC1 bio-optical algorithms, respectively. The standard SeaWiFS surface chlorophyll-a concentration represents the OC4 bio-optical algorithm.

4. ELF calibration of the SeaWiFS and MODIS bio-optical algorithms

Examples of ELF calibration of the SeaWiFS bio-optical algorithm have been already published elsewhere (Barbini *et al.* 2001b, 2003, Colao *et al.* 2002), hence here we will only recall its main features. Although the standard SeaWiFS bio-optical algorithm (OC4) is based on a modified cubic polynomial applied to four bands we decided to use a linear approach applied to two bands (OC1) (O'Reilly *et al.* 1998). In fact, figure 5 shows a large dispersion of the ELF measurements and, as in earlier works (Mitchell and Holm-Hansen 1991, Mitchell 1992), it did not seem reasonable to use higher order polynomials and/or more bands, and therefore the ELF-calibrated bio-optical algorithm has been based on the linear fit of the log–log plot of the lidar concentration versus the 490–555 band ratio. Higher-order polynomials would have led to an unstable fit, more bands would have introduced an unjustified complication as demonstrated by figure 5. At least in our case, standard OC1 and standard OC4 are very close and thus the departure of ELF-calibrated OC1 from standard OC1 gives a good estimate of the discrepancy between ELF-calibrated and standard surface chlorophyll-a concentrations.

OC1 is expressed by (O'Reilly *et al.* 1998)

$$C = 10^{a_0 + a_1 R} \tag{5}$$

where C is the chlorophyll-a concentration in $\mathrm{mg\,m^{-3}}$ and

$$R = \log_{10} \frac{\mathrm{R_{rs}(490\,nm)}}{\mathrm{R_{rs}(555\,nm)}} \tag{6}$$

Table 3. Parameters of some bio-optical algorithms considered in this study (the standard deviations of the parameters of standard OC1 are not given in the literature).

	a_0	a_1
Standard OC1	0.3734	–2.4529
ELF-calibrated OC1 (SeaWiFS)	–0.086 ± 0.025 (29%)	–2.076 ± 0.055 (3%)
ELF-calibrated OC1 (MODIS)	–0.028 ± 0.023 (82%)	–1.359 ± 0.048 (4%)

The parameters of the ELF-calibrated OC1 and standard OC1 are summarized in table 3.

Let us note that the difference between ELF-calibrated OC1 and standard OC1 is larger than the error bar (the standard deviations of the parameters of standard OC1 are not given in the literature). ELF-calibrated OC1 provides lower concentrations, thus correcting the tendency of SeaWiFS to overestimate chlorophyll-a at these low concentrations. This can be checked plotting C_L/C_S as a function of C_L, as in figure 4, but now with C_S computed with ELF-calibrated OC1 (figure 6). Comparing figures 4 and 6, one can observe that ELF-calibrated OC1 pushes C_L/C_S nearer to unity and reduces the dispersion. In particular, thanks to ELF-calibrated OC1, the average value of C_L/C_S changes from 0.58 to 1.10, the standard deviation from 0.29 to 0.53, i.e. from 50% to 48%. The departure of C_L/C_S from unity is no more larger than the error bar. However, this approach is obtained at the price of a slight underestimation by ELF-calibrated OC1 of the higher concentrations: (1) For C_L from 0 to 0.15 mg m^{-3} (621 points), the average value and the standard deviation of C_L/C_S are now 0.96 and 0.40, respectively (departure from unity is not

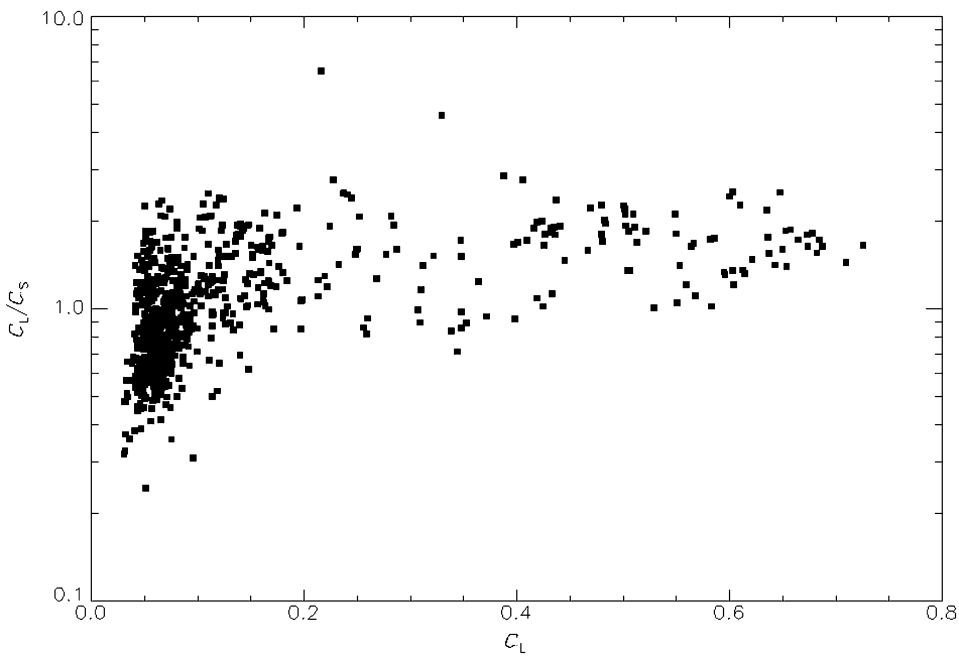

Figure 6. Ratio between the surface chlorophyll-a concentration measured by ELF and SeaWiFS (with the ELF-calibrated OC1 bio-optical algorithm) versus the surface chlorophyll-a concentration measured by ELF.

larger than the error bar). (2) For C_L from 0.15 to 0.75 mg m^{-3} (163 points), the average value and the standard deviation of C_L/C_S are 1.63 and 0.63, respectively (departure from unity is not larger than the error bar).

Let us note that low and high concentrations are the 79% and 21% of the sample, respectively, and thus a better performance for C_L from 0 to 0.15 mg m^{-3} is preferable. We can conclude that, in our case, ELF-calibrated OC1 approaches more than OC4 to the *in situ* data (i.e. C_L/C_S is closer to unity after the application of ELF-calibrated OC1, rather than OC4, to the SeaWiFS data). For this reason, we used ELF-calibrated OC1 to draw a map of concentration (figure 7), based on the average of the daily satellite sensor data acquired during the entire cruise.

The difference between OC4 and ELF-calibrated OC1, normalized by OC4, is shown in figure 8. In oligotrophic regions, this difference is small (0–25%) whereas in mesotrophic regions is larger (50–75%). These values, in full agreement with table 2, confirm that ELF-calibrated OC1 corrects the tendency of SeaWiFS to overestimate chlorophyll-a.

In the way we have obtained ELF-calibrated OC1 for SeaWiFS, we can do the same for MODIS: it is sufficient to substitute the MODIS band ratio to the SeaWiFS band ratio in the fit of the lidar chlorophyll-a versus the radiometer band ratio, according to equation (5). Actually, MODIS measures Rrs at 488 and 551 nm, but this slight difference is negligible for this analysis. The parameters of the ELF-calibrated OC1 and standard OC1 are summarized in table 3. As for SeaWiFS, in our case, ELF-calibrated OC1 performs better than the standard MODIS bio-optical algorithm. Once more, we used ELF-calibrated OC1 to draw a map of concentration (figure 9), based on the average of the satellite daily data acquired during the entire cruise. The chlorophyll-a images are quite similar for the two radiometers. However, SeaWiFS and MODIS performances differ mainly as follows:

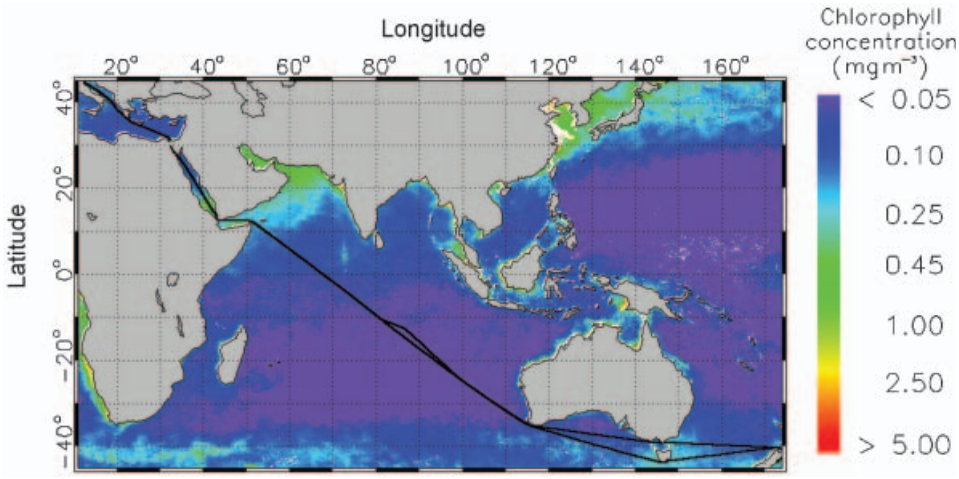

Figure 7. Surface chlorophyll-a concentration measured by SeaWiFS with the ELF-calibrated OC1 bio-optical algorithm during the Italy–New Zealand and New Zealand–Italy transects (13 November–18 December 2001 and 28 February–1 April 2002, respectively). Thick black line: ship track.

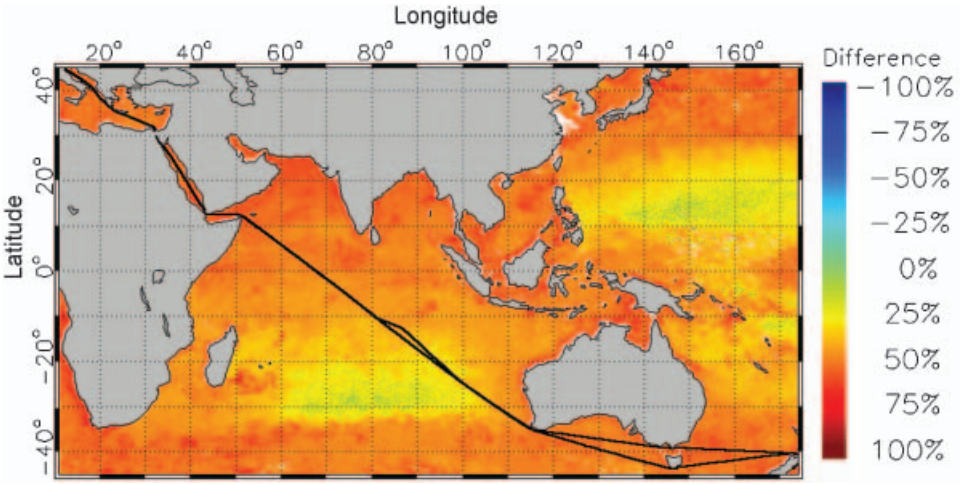

Figure 8. Per cent difference between the surface chlorophyll-a concentration measured by SeaWiFS with the standard and ELF-calibrated OC1 bio-optical algorithms during the Italy–New Zealand and New Zealand–Italy transects (13 November–18 December 2001 and 28 February–1 April 2002, respectively). Thick black line: ship track.

1. with respect to SeaWiFS, MODIS data are more patchy, in agreement with the higher standard deviation and the more fluctuating behaviour we have already observed (table 2 and figure 3);
2. with respect to SeaWiFS, the MODIS dynamic range is more compressed: chlorophyll-a is higher (lower) in oligotrophic (mesotrophic) regions; and
3. MODIS products are available also in some coastal zones where the SeaWiFS processing fails.

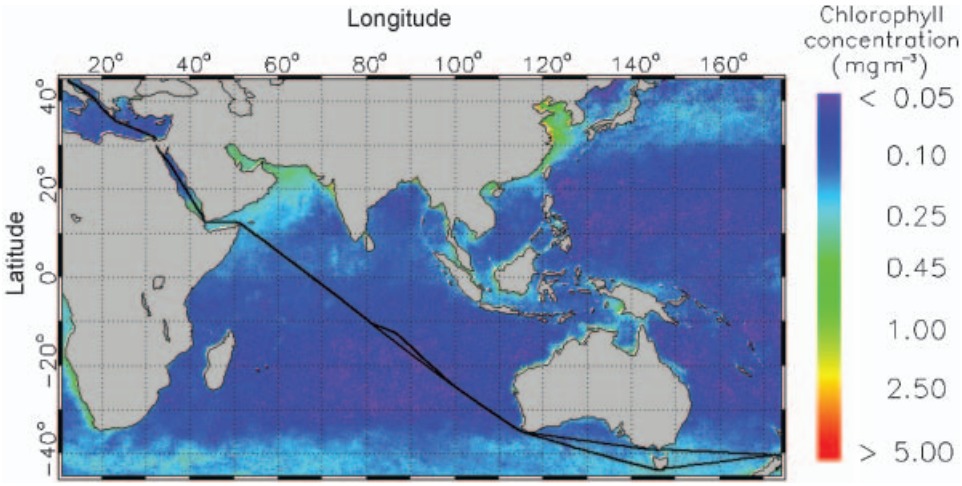

Figure 9. Surface chlorophyll-a concentration measured by MODIS with the ELF-calibrated OC1 bio-optical algorithm during the Italy–New Zealand and New Zealand–Italy transects (13 November–18 December 2001 and 28 February–1 April 2002, respectively). Thick black line: ship track.

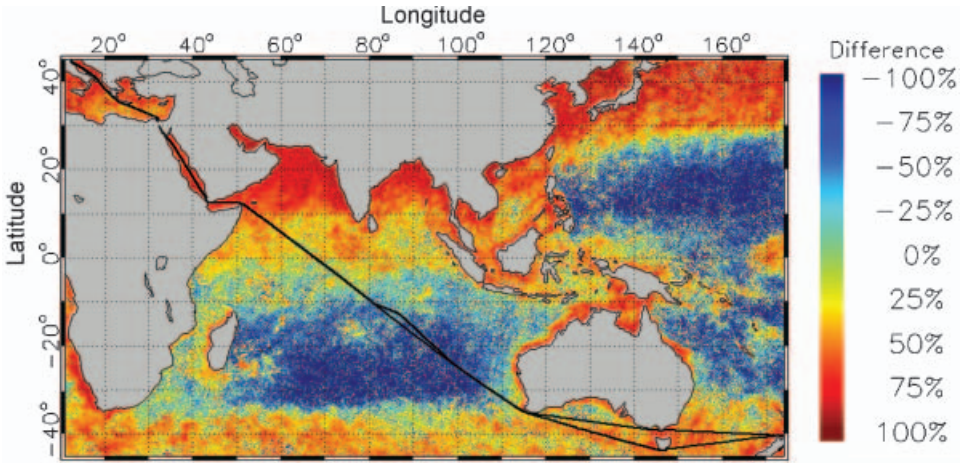

Figure 10. Per cent difference between the surface chlorophyll-a concentration measured by MODIS with the standard and ELF-calibrated OC1 bio-optical algorithms during the Italy–New Zealand and New Zealand–Italy transects (13 November–18 December 2001 and 28 February–1 April 2002, respectively). Thick black line: ship track.

The difference between the standard MODIS bio-optical algorithm and ELF-calibrated OC1, normalized by the standard MODIS bio-optical algorithm, is shown in figure 10. With respect to the analogous analysis on SeaWiFS data, this difference assumes both signs and reaches high absolute values (up to 100%). In any case, the large fluctuation of MODIS data implies that these differences are inaccurate and therefore should be regarded with caution as a few points can bend considerably the linear fit. While the patchy appearance of figure 9 is linked to the fluctuation of MODIS data, the irregular appearance of figure 10 is due to the discrepancy between the bio-optical algorithms: apart from the absolute values of the differences, the standard MODIS bio-optical algorithm and ELF-calibrated OC1 can perform very differently in neighbouring pixels: this is not surprising because their principles are very dissimilar.

5. Conclusions

ELF carried out measurements of surface chlorophyll-a concentration continuously, except for rare and short maintenance stops, during the Italy–New Zealand and New Zealand–Italy transects (13 November–18 December 2001 and 28 February–1 April 2002, respectively).

After a degradation of their temporal and spatial resolution, these measurements have been compared with the concurrent L3 data of SeaWiFS and MODIS. This study revealed that ELF was able to carry out measurements on many occasions when SeaWiFS and MODIS were not. Moreover, due to its finer resolution, ELF performed better in the detection of local anomalies.

The ELF measurements, after calibration with conventional analyses on the same water performed during the RV cruise, have been related with the SeaWiFS and MODIS data. The radiometers, compared with lidar, showed the tendency to overestimate chlorophyll-a at the low concentrations found during the MIPOT campaign. The overall agreement between lidar and radiometers was good, especially for high concentrations. In our case, this performance has been further

improved by the calibration of the SeaWiFS and MODIS bio-optical algorithm with the ELF data.

The results of this study emphasize the importance of *in situ* sensors for continuous calibrations and validations of satellite sensor data and for measurements of surface chlorophyll-a concentrations when the data processing of spaceborne radiometers fails (turbid water, cloud coverage, etc.).

The comparison between the two radiometers revealed that SeaWiFS products had a fluctuation lower than MODIS products. On the other hand, the SeaWiFS atmospheric correction method failed in some coastal zones where MODIS was able to take measurements.

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