COMBINATION OF LIDAR, MODIS AND SEAWIFS SENSORS FOR SIMULTANEOUS CHLOROPHYLL MONITORING

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ABSTRACT

Ocean colour satellites have changed our way to observe the Earth: Planetary maps of the surface chlorophyll-a concentration, and hence of the phytoplankton primary productivity, can be retrieved in few days. Nevertheless, these results are the product of complex calculations: Atmospheric corrections and bio-optical algorithms 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, usually operated from marine buoys, fixed stations, and research vessels (RVs).

The ENEA lidar fluorosensor (ELF), aboard the RV *Italica*, is one of the shipboard lidar devoted to oceanographic studies. It 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). This study is part of the MIPOT (Mediterranean Sea, Indian and Pacific Oceans Transect) oceanographic campaign and provided the "sea truth" in less studied marine zones (Red Sea and Indian Ocean).

As in previous lidar-satellite comparisons, the ELF measurements were compared to the imagery collected by SeaWiFS and 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 data. The differences between the performances of the two satellite sensors are also briefly discussed.

Keywords: lidar fluorosensor, ocean colour satellite, calibration/validation, chlorophyll-a

INTRODUCTION

The ocean plays a major role in shaping the climate of our planet by regulating the global cycles of elements such as carbon. Scientists study the chlorophyll-a distribution to understand the natural processes that control the size and distribution of the ocean carbon reservoir.

More than 40 years after the discovery of the laser, laser remote sensors (1) and, in particular, hydrospheric lidars (2,3,4,5) are mature systems. Also Earth observation satellites (6) are reliable instruments now. In particular, ocean colour radiometers (7) provided us with an unprecedented insight into the phytoplankton dynamics. Unfortunately, their data are not free from uncertainties. On the one hand, atmospheric corrections (8) are necessary to obtain water-leaving radiances, removing from the radiometer measurements the contributions of air molecules and aerosols, which represent up to 90% of the signal intensities in the visible bands. On the other hand, the bio-optical algorithms (9), i.e. the set of semi-empirical equations used to calculate biogeochemical properties from the water-leaving radiances in the visible bands, have to be calibrated with *in situ* measurements, because they do not represent all the provinces of the world oceans.

This may explain why some models wrongly estimate primary production: e.g. in the Southern Ocean. Some calculations suffer from the "Antarctic paradox", i.e. the evaluated primary production is insufficient to support the population of grazers (10). The important consequences of those

studies on the fate of our planet, justifies the efforts of assessing ocean colour data sensed from spaceborne radiometers with "sea truth" provided by *in situ* measurements.

In this framework, the ENEA lidar fluorosensor (ELF) (11), operational aboard the research vessel (RV) *Italica* during four Italian expeditions in Antarctica (13th, 15th, 16th and 18th in 1997-98, 2000, 2001, and 2003) and the MIPOT (Mediterranean Sea, Indian and Pacific Oceans Transect) oceanographic campaign (2001-02), gathered a large amount of data useful for the validation and/or the calibration of spaceborne radiometers.

Figure 1: Main picture: RV Italica; ELF and the ancillary instruments are housed in a container (inside the circle). Left insert: external view of the container; note on the right of the container the box accommodating the mirror for water surface observation. Right insert: internal view of the container; ELF is visible on the left of the operator.

METHODS

ELF (Figure 1) consists mainly of a frequency-tripled Q-switched Nd:YAG laser (transmitter) and of a Cassegrain telescope coupled to detectors (receiver). The laser emits pulses to the sea surface and the telescope collects the backscattered light at different wavelengths. The radiation is then directed through a fiber bundle to spectral bandpass filters and is detected with photomultiplier tubes. Other instruments provide ancillary measurements: lamp spectrofluorometer, pulsed amplitude fluorometer, solar radiance detector and global positioning system (GPS). The specifications of ELF are summarized in table 1.

ELF excites water with a laser pulse at 355 nm and observes the Raman backscattering of water at 404 nm and the fluorescence of chromophoric dissolved organic matter (CDOM) at 450 nm, phycoerytrin at 575 nm and chlorophyll-a at 680 nm. An example of those measurements during the MIPOT campaign is given in Figure 2.

The absolute concentrations of the pigments are directly proportional to the fluorescence-to-Raman ratios (also known as concentrations released in Raman units) (12). The Raman units are then converted into 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 (13) according to the spectrofluorometric technique described by Lorenzen and Jeffrey (14). Finally, the data are geo-referenced with the GPS and released in thematic maps (Figure 3). ELF error on chlorophyll-a concentration is 25% (12).

Table 1. Specifications of ELF.

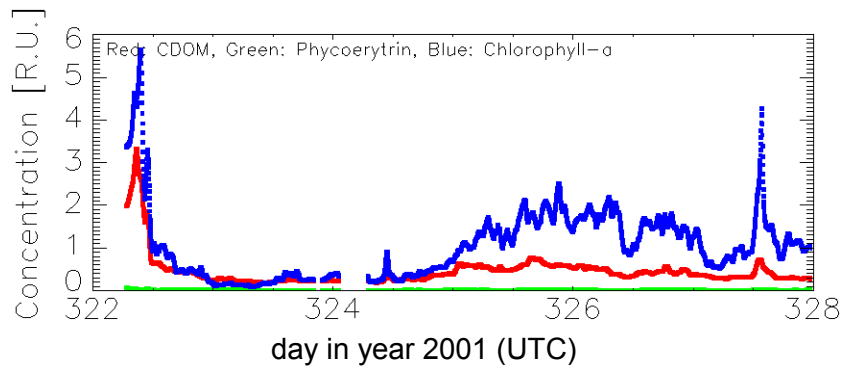|		
Transmitter	Wavelength	355 nm
	Pulse energy	3 mJ
	Pulse duration	10 ns
	Pulse repetition rate	10 Hz
Receiver	Clear aperture	0.4 m
	Focal length	1.65 m
	Centre wavelengths	404, 450, 585, 680 nm
	Bandwidths	5 nm FWHM
Electronics	Detectors	Photomultipliers
	Gate width	100 ns
	Dynamic range	15 bit
	Central Processing Unit	VME embedded 486

Figure 2: Concentration of CDOM (red), phycoerytrin (green) and chlorophyll-a (blue) during the period from 18 to 23 November 2001.
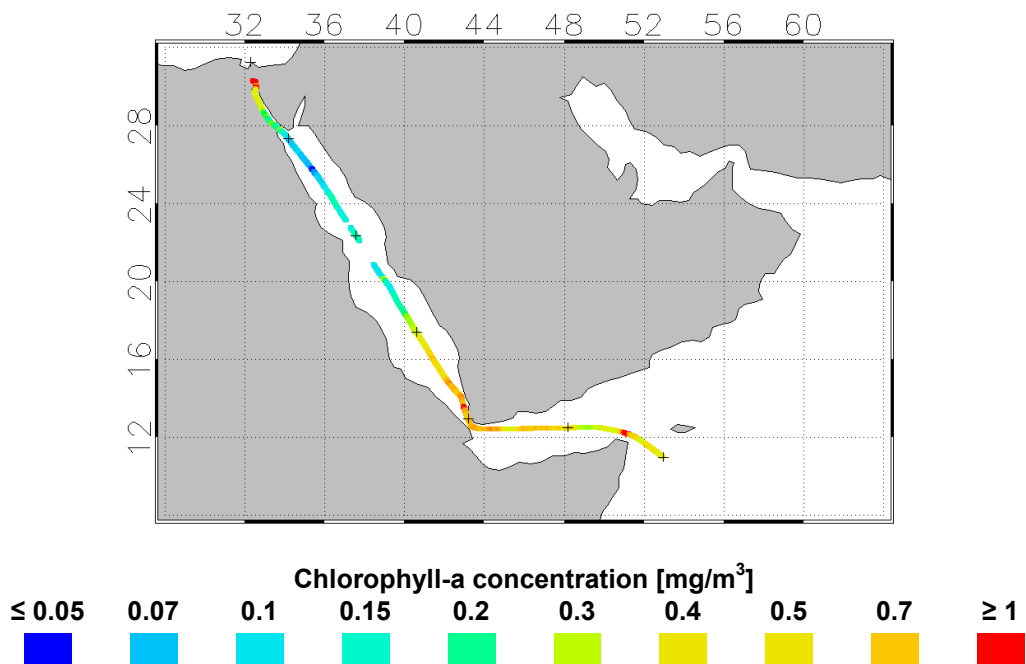

Figure 3: Thematic map of chlorophyll-a during the period from 18 to 23 November 2001.

The first ocean colour radiometer was CZCS (15), operated on the Nimbus-7 satellite from 1978 to 1986. Four new ocean colour radiometers, SeaWiFS (16), two MODIS sensors (17) and MERIS (18), were launched on 1 August 1997, 18 December 1999, 4 May 2002, and 1 March 2002, respectively. The first, aboard OrbView-2, is a joint venture of Orbital Sciences Corporation and the National Aeronautics and Space Administration (NASA). The two MODIS sensors, integrated on Terra and Aqua, respectively, are part of the NASA's Earth Observing System (EOS), a program including six spacecrafts: Aqua, Aura, ICESat, Landsat 7, SORCE and Terra. MERIS is one of the instruments aboard ENVISAT, an important Earth observing satellite of the European Space Agency (ESA).

Modern ocean colour radiometers have been designed mainly for the observation of phytoplankton biochemistry: In particular, they are expected to provide surface chlorophyll-a concentrations over the range from 0.05 to 50 mg m^{-3}. The main characteristics of SeaWiFS, MODIS and MERIS are summarized in table 2.

Table 2. Main characteristics of SeaWiFS, MODIS and MERIS

Radiometer	SeaWiFS	MODIS	MERIS
Scan Width	±58°.3[a], ±45°.0[b]	±55°	±34°.25
Scan Coverage	2,800 km[a], 1,500 km[b]	2,330 km	1,150 km
Nadir Resolution	1.13 km[a], 4.5 km[b]	0.25 km[c], 0.5 km[d], 1 km[e]	0.3 km[f], 1.2 km[g]
Bands	8 (412 – 865 nm)	36 (405 – 14,385 nm)	15 (412.5 – 900 nm)
Tilt	20°, 0°, +20°	No	No
Digitization	10 bits	12 bits	12 bits
Date of first acquisition	4 September 1997	24 February 2000[h]	22 March 2002

[a] Local area coverage.   [e] Bands 8 – 36
[b] Global area coverage.   [f] Full resolution.
[c] Bands 1 – 2   [g] Reduced resolution.
[d] Bands 3 – 7   [h] For MODIS aboard Terra; 24 June 2002 for MODIS aboard Aqua.

RESULTS

During MIPOT, SeaWiFS and MODIS on Terra were operational and the RV *Italica* covered the Italy – New Zealand and New Zealand – Italy transects providing *in situ* data for 69 days continuously (13 November – 18 December 2001 and 28 February – 1 April 2002, respectively) in less studied marine zones (Red Sea, Indian Ocean).

The temporal and spatial resolutions of ELF, SeaWiFS, and MODIS are very different: While an accurate lidar measurement requires about 1 minute corresponding to a track about 0.5 km long and 0.1 m wide (as a consequence of averaging 600 laser pulses and of the 0.1 m beam footprint), a satellite swath is acquired within some minutes and a radiometer pixel size around 1 km. The temporal and spatial resolution of spaceborne sensors degrades further passing from raw to processed imagery. In this study, Level 3 (L3) daily Standard Mapped Image (SMI) products were used both for SeaWiFS and MODIS and only non-questionable pixels were retained. L3 is the highest processing level for chlorophyll-a and ensures the best accuracy, 1 day is the finer temporal resolution for L3 files and SMI products of SeaWiFS and MODIS are readily comparable (one SeaWiFS pixel contains exactly four MODIS pixels). As far as depth is concerned, lidar and radiometers probe to a depth in the order of 10 m (this is only a guide value as light penetration is a strong function of wavelengths and suspended or dissolved materials). The sensitivity of the telescope versus distance is optimised in order to probe that surface layer, which is done by collecting the light coming from the telescope by a large optical fiber bundle (10 mm diameter).

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 two radiometers had the same temporal and spatial resolution (1 day and about 9 km × 9 km, respectively); from now on, this

average is denoted as "MODIS pixel". Secondly, all the ELF measurements falling in a SeaWiFS pixel were averaged, thus representing a nearly straight track (length: ~ 5-10 km, width: ~0.1 m) acquired in about 10-20 minutes: in the following, this track is denoted as "ELF granule". In general, strong variations in the chlorophyll-a concentrations along the ship track were not observed for short distances (less than 10 km). This suggests that also in a direction perpendicular to the track the concentrations are homogeneous enough for a comparison with a radiometers pixel, especially in open oceanic zones.

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. As a consequence, the temporal difference between lidar and radiometers sampling is less than 24 hours, a short time when compared with the phytoplankton dynamics in open oceanic zones.

The remaining dissimilarity in temporal and spatial resolutions can hardly be avoided and may be responsible for part of the disagreement between SeaWiFS and ELF, especially in the Red Sea where chlorophyll concentrations may vary significantly during 24 hours. Moreover, the lidar - radiometers comparison should be taken cautiously in coastal zones, because ocean colour sensor algorithms perform poorly in such regions. The concurrent measurements of surface chlorophyll-a concentration carried out by ELF (C_L), SeaWiFS (C_S), MODIS with the SeaWiFS bio-optical algorithm (C_{MS}), and MODIS with the standard bio-optical algorithm (C_M) are shown in Figure 4.

On many occasions, ELF was able to carry out measurements when SeaWiFS and MODIS data were not available: During the entire cruise, 9,086 ELF granules were collected and only 1,318 of them were concurrent to at least one radiometer pixel (784 with a SeaWiFS pixel and 695 with a MODIS pixel). This partial failure of the spaceborne sensors is probably due to cloud coverage, lasting for many days, especially in the Indian Ocean, and to the 10-day shut down of MODIS in March 2002.
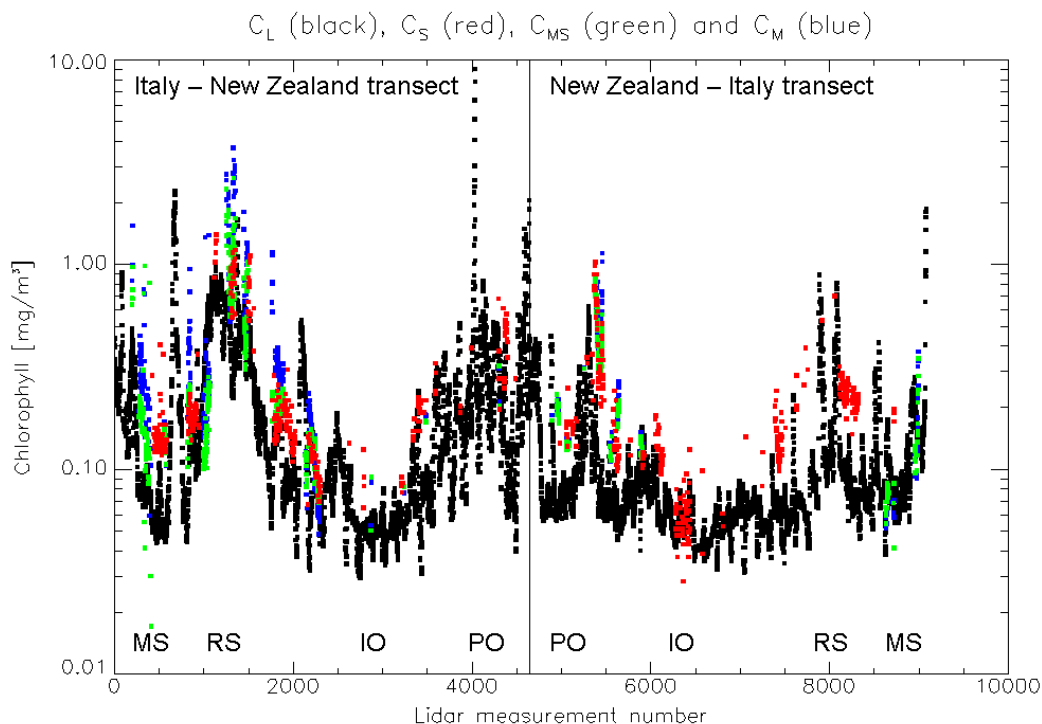

Figure 4. Surface chlorophyll-a concentration measured by ELF (C_L), SeaWiFS (C_S), MODIS with the SeaWiFS bio-optical algorithm (C_{MS}), and MODIS with the standard bio-optical algorithm (C_M). MS: Mediterranean Sea; RS: Red Sea; IO: Indian Ocean. PO: Pacific Ocean.

Figure 4 suggests that ELF performed better in the detection of steep peeks, probably because of the residual 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 7 cases [during the Italy – New Zealand transect: in

coastal waters of the Mediterranean Sea (lidar measurement number ~ 100), in the Suez Channel (lidar measurement number ~ 700), in coastal waters of the Red Sea (lidar measurement number ~ 1300), in the Hobart Harbour (lidar measurement number ~ 4000) and in coastal waters near New Zealand (lidar measurement number ~ 4600); during the New Zealand – Italy transect: in coastal waters of the Red Sea (lidar measurement number ~ 7900) and in coastal waters of the Mediterranean Sea (lidar measurement number ~ 9100)], while C_S and C_M, apart from isolated points are high in two cases [during the Italy – New Zealand transect: in coastal waters of the Red Sea (lidar measurement number ~ 1300); during the New Zealand – Italy transect: in coastal waters of the Pacific Ocean (lidar measurement number ~ 5400)].
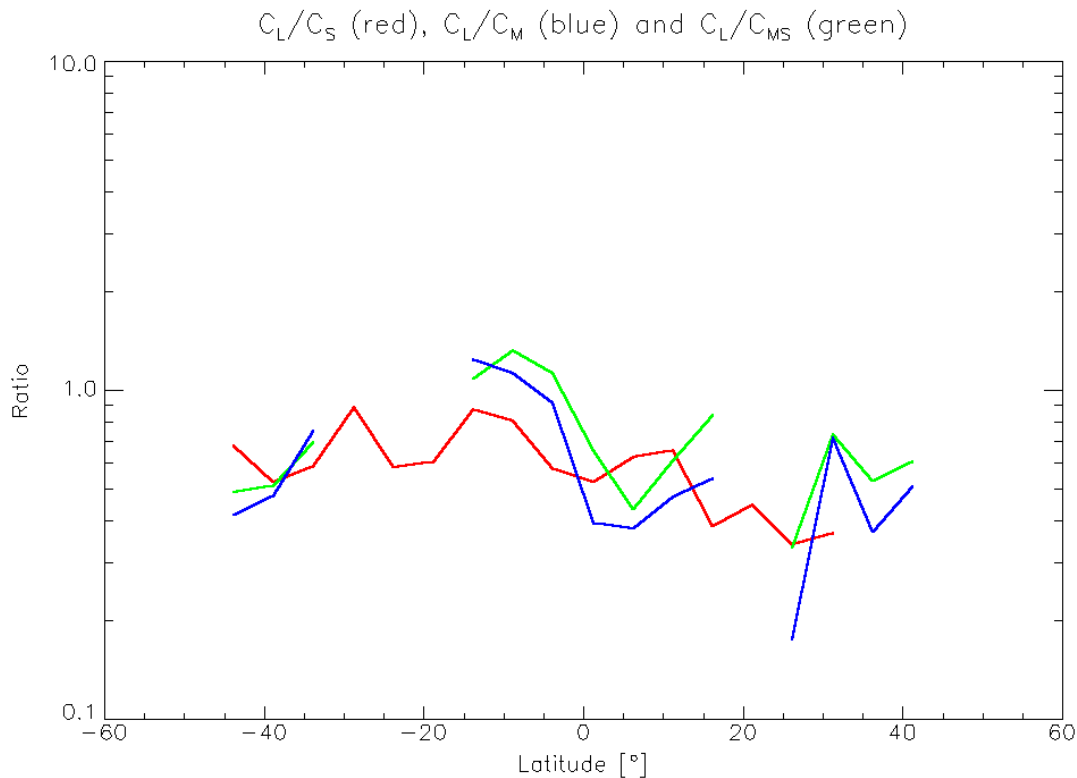

Figure 5: C_L/C_S, C_L/C_{MS} and C_L/C_M as a function of the latitude.

Although C_S and C_M are in general higher than C_L, the overall agreement between lidar and radiometers is good: All the sensors show strong concentrations in the Mediterranean Sea, the Red Sea and the Pacific Ocean, especially in the Italy – New Zealand transect. As one can expect, C_{MS} is closer to C_S than C_M. This means that the disagreement between SeaWiFS and MODIS is related not only to water-leaving reflectance discrepancies but also to bio-optical algorithm differences (19).

In order to better understand the different behaviour of ELF, SeaWiFS, and MODIS, the ratios C_L/C_S, C_L/C_{MS} and C_L/C_M have been plotted as a function of the latitude (figure 5). While, in general, the satellite-derived concentrations are overestimated, MODIS is lower than ELF in oligotrophic waters (Indian Ocean, latitude: 0° – -15°). The discrepancy between lidar and spaceborne sensors is of the order of 25% on an average. This value is comparable to the final accuracy of the chlorophyll-a retrieval by SeaWiFS (20).

A way to improve our understanding of the phytoplankton dynamics is to calibrate the bio-optical algorithms used by satellite radiometers with the measurements performed by *in situ* instruments. This approach has already been undertaken for SeaWiFS and ELF (21) to obtain new estimates of chlorophyll-a concentration and primary production in the Southern Ocean (22).
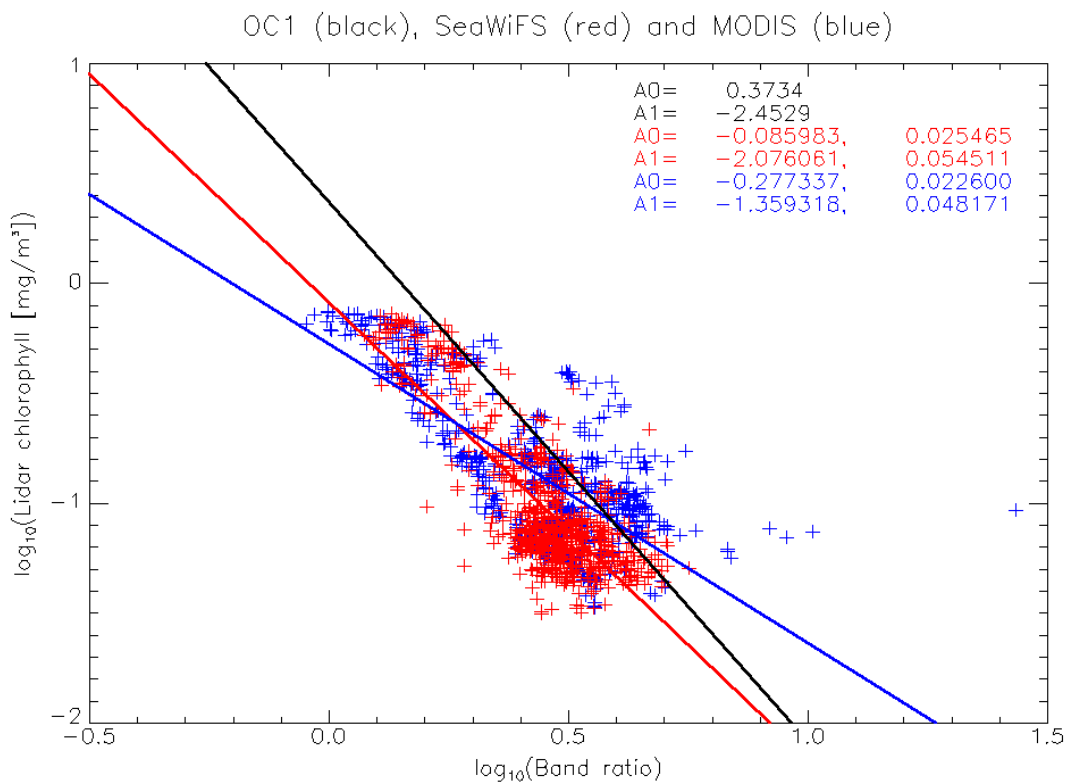
Figure 6: OC1 (black line), ELF-calibrated SeaWiFS (red line) and ELF-calibrated MODIS (blue line) bio-optical algorithms.

The calibration of the bio-optical algorithm is accomplished by a linear fit of the points $\{\log_{10}(C_L),$ $\log_{10}[Rrs(\lambda_1)/Rrs(\lambda_2)]\}$ where $Rrs(\lambda)$ is the remote sensing reflectance measured by a satellite radiometer (λ_1 is 490 and 488 nm for SeaWiFS and MODIS, respectively and λ_2 is 555 and 551 nm for SeaWiFS and MODIS, respectively). The results, compared to the standard OC1 (9) bio-optical algorithm (Figure 6) show that SeaWiFS overestimates especially the high concentrations, while MODIS underestimates in oligotrophic waters (chlorophyll-a lower than about 0.1 mg m^{-3}) and overestimates in mesotrophic and eutrophic waters (chlorophyll-a higher than about 0.1 mg m^{-3}). Note that a similar behaviour is already observed in Figure 5.

Eventually, the ELF-calibrated bio-optical algorithms can be used to correct the standard SeaWiFS and MODIS chlorophyll-a maps (Figs. 7a,b). The differences between standard and corrected maps for SeaWiFS and MODIS (Figs. 7c,d) demonstrate once more that SeaWiFS overestimates (0 – 50%) especially in eutrophic waters, while MODIS shows underestimations up to -75% for low concentrations and overestimations up to 75% for high concentrations. These results suggest the need of a regional bio-optical algorithm, particularly for MODIS. It should be noted also that MODIS data seem less reliable because of their patchy appearance (fluctuation). On the other hand, MODIS takes measurements also in some coastal zones (e.g. between China and Korea), where SeaWiFS fails regardless of the bio-optical algorithm (OC1 or OC4).

CONCLUSIONS AND PERSPECTIVES

Remote sensing data provided by laser systems and satellite radiometers can be combined, thus merging their advantages (accuracy of the laser systems and coverage of the satellite radiometers). Moreover, shipboard instruments can provide information even when the remote sensors fail (e.g. in some coastal zones or in case the sea is screened by clouds).
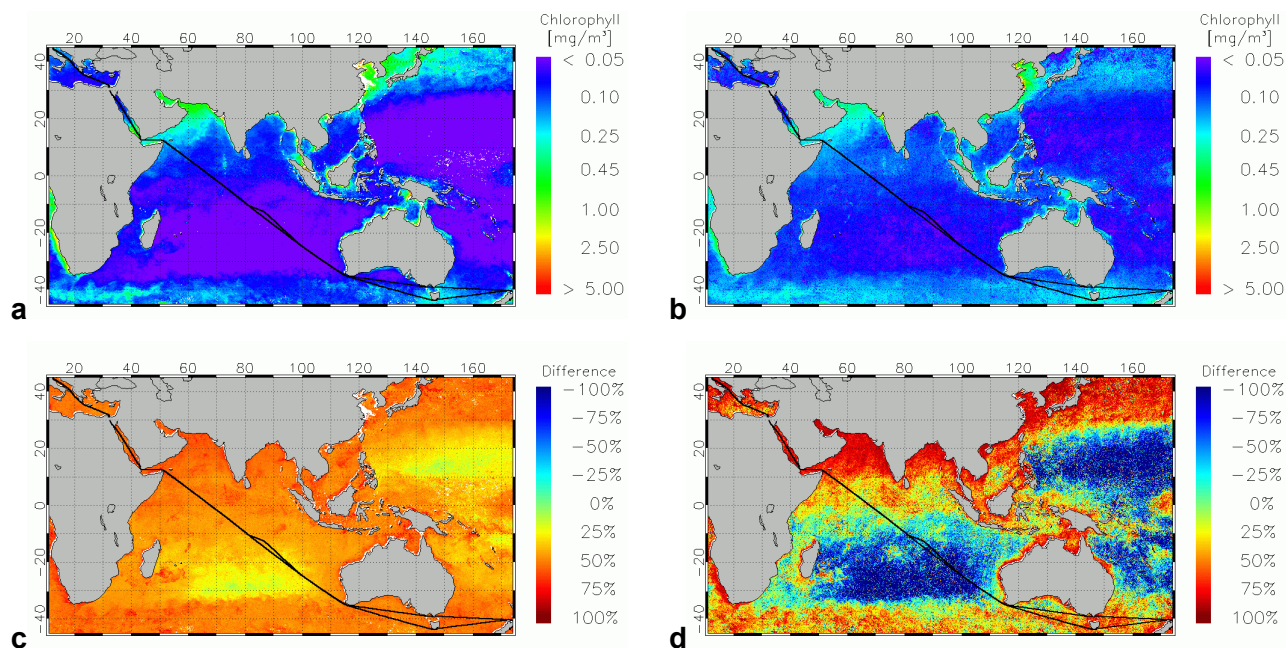
Figure 7: a) Standard SeaWiFS chlorophyll-a map. b) Standard MODIS chlorophyll-a map. c) Difference between standard and corrected SeaWiFS chlorophyll-a maps. d) Difference between standard and corrected MODIS chlorophyll-a maps. Black lines: ship tracks.

The comparison of the imagery provided by SeaWiFS and MODIS with the measurements performed by ELF suggests that the final accuracy in the chlorophyll-a concentration is of the order of 25%. Although this result is in good agreement with literature data (19,20), it should be regarded as preliminary. Possible sources of systematic and random differences between SeaWiFS, MODIS, and ELF should be investigated in more detail.

Nevertheless, as a heuristic exercise, the SeaWiFS and MODIS bio-optical algorithm has been calibrated with the ELF data. The results indicate that new regional algorithms could give better estimates of primary production in the oceanic waters. This improvement in monitoring accuracy and coverage achieved by the simultaneous operation of lidar fluorosensors and spaceborne sensors could solve some problems of the present primary production models.

Another interesting perspective is the correction of satellite data for effects of CDOM absorbance, which reduces the depth range seen by the satellite. This issue can be better addressed by lidar, since CDOM is not easily detected by radiometers.

ACKNOWLEDGEMENTS

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