

RANGE RESOLVED LIDAR FLUOROSENSOR FOR MARINE INVESTIGATION

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ABSTRACT

Shipborne and airborne lidar fluorosensors are currently in use to monitor wide marine surfaces. Important seawater quality parameters can be remotely monitored, such as phytoplankton and CDOM concentration, turbidity and pollutants. Since marine organic substances and phytoplankton are stratified in layers floating at different water depths, it is of primary importance for exhaustive ecosystem studies to measure their vertical concentration profiles. A new lidar fluorosensor has been designed and developed in the frame of the Italian Research Program for Antarctica, to remotely detect these seawater features in a range resolved mode. The system has been mounted in the hold of the research vessel *Italica* and connected to the lower sea water level through a large size tube down to the ship's keel. Subsurface waters were investigated starting from about 7 m depth. Full operation was achieved during the XV Italian Antarctic Expedition: range resolved LIF signals were collected on four spectral channels, corresponding to laser back-scattering, water Raman, CDOM and Chl-a emission, respectively. Total extinction and information on concentrations depth profiles could be extracted from the data. Different tests were performed on the hardware to gain information about the transceiver and electronic modules. Results of the system performances in terms of range and sensitivity for each spectral channel will be utilised in designing a new compact lidar fluorosensor package to be mounted on an underwater Remotely Operated Vehicle.

INTRODUCTION

The Southern Ocean surrounding Antarctica represents a mosaic of different marine subsystems, which include large basins, such as the Antarctic Ross Sea and the Weddel Sea, and coastal areas, like the Terra Nova Bay nearby the Italian base. Most of the dynamical phase in the seawater takes place during the austral summertime, due to the seasonal temperature rise in combination with strong katabatic winds. The combination of these effects provokes the pack-ice breaking and melting with the occurrence of intense phytoplankton blooms, especially in polynya or coastal areas. These phenomena have a strong influence on the seawater vertical stability, where, following the input of less saline and dense melt waters, nutrient depletion and biogenic matter production simultaneously occur. Also humic substances are known to play a major role in the biogeochemical processes taking place in coastal and offshore waters, including transport and speciation of trace metals (1). The phytoplankton activity, influenced both by the sunlight intensity and the nutrient availability, is responsible for the different stratification and the accumulation of organic matter with changes in its biochemical composition (2). The organic matter flux released in the deeper layers is primarily affected by the natural Antarctic biosystem, where the phytoplankton community, mainly dominated by diatoms and *Phaeocystis Antarctica*, is the first ring of the food chain for zooplankton, fish, whales, seals and birds (Figure 1).

Finally, the dynamical variations of biological and hydrological seawater parameters are of particular interest for a better understanding of the interaction with the surrounding environment, including the atmospheric CO₂ uptake (3), which in turn governs the climatic evolution of the planet.

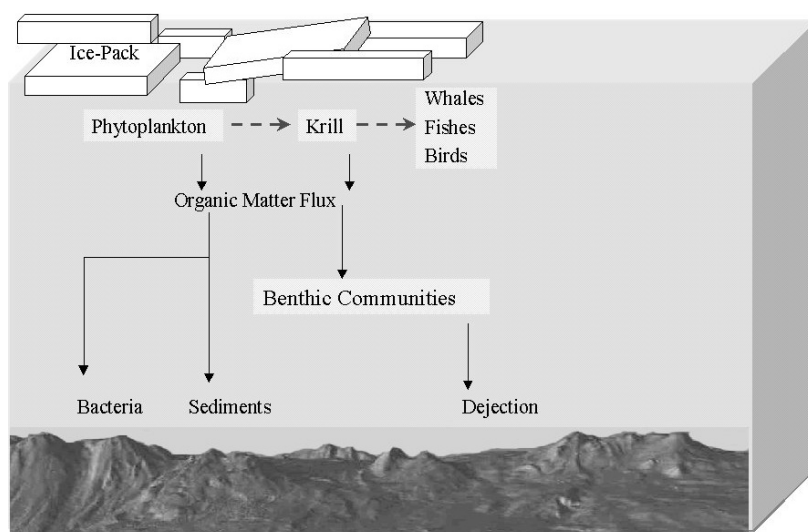


Figure 1: Synopsis of Antarctic marine ecosystem and its biogeochemical cycles

In this connection, remote and range resolved techniques suitable to detect seawater chromophores *in vivo*, without any need of sample concentration or extraction, are especially valuable for broad investigation. Spectrally resolved fluorescence measurements are among the most versatile methods for this kind of field application. Signatures of dispersed impurities, such as crude oils, protein-like (amino-acids) and humic-like substances (Chromophoric Dissolved Organic Matter: CDOM) and phytoplankton, can be extracted from fluorescence excitation and emission spectra of seawater samples in the UV to visible range (4,5). Local fluorescence data can be converted into absolute concentrations after calibration against conventional chemical measurements, and further used to calibrate the corresponding spectral channels in remotely sensed measurements based either on active lidar or passive systems (6).

The ENEA laser remote sensing group in Frascati has already developed an integrated LIF (Laser Induced Fluorescence) laboratory in the frame of the Italian National Research Programme for Antarctica (PNRA). A mobile laboratory, whose heart includes a lidar fluorosensor and a lamp spectrofluorometer has been assembled and installed in the R/V *Italica* in order to permit the continuous and automatic remote monitoring of surface seawater quality and phytoplankton. During its participation to the XIII Italian Antarctic Expedition (Nov. '97-Jan. '98), thematic maps of different surface seawater parameters based upon lidar fluorosensor data measured on different emission channels, have been obtained and discussed in (7, 8).

The present paper deals specifically with the realisation of a new apparatus for range resolved measurements, aimed to monitor vertical concentration profiles of dissolved organic substances and phytoplankton, along water columns. The new version has been installed directly on the afterhold of the R/V *Italica* and has already participated to the XV campaign (Jan-Feb 2000) for operational tests and a cross calibration against a surface lidar fluorosensor simultaneously operated. The time resolved operation on each fluorescence signal, giving a depth profile measurement on the corresponding channel, is the main innovative feature of this apparatus (9).

The LIF technique for marine applications

The LIF collected upon UV excitation, contains spectral signatures of dispersed or dissolved organic matter, such as crude oils, CDOM and phytoplankton. LIF measurements assume a direct correlation existing between the light intensity emitted at a given wavelength and the concentration of the chromophore molecules contained in the excited target (10). The signal intensity actually detected depends on a number of system parameters such as wavelength, pulse energy and duration, diver-

gence of the exciting laser; optical transmission of lenses, fiber-optics and filters in the receiver subunit; detector (OMA, PMT) spectral sensitivity, the optical extinction of the crossed media (air, water, biological tissues) at the excitation and detection wavelengths, and finally the optical properties of the considered chromophores (5).

In the case of a pulsed lidar, the received signal contains different spectral signatures related to the physical interaction between the laser and the molecular constituents of the investigated target. To the received signal contribute the elastic (Rayleigh or Mie) and inelastic (Raman) scattering phenomena, while fluorescence is mainly related to *hydrosols*, liquid or solid suspended particles, commonly distinguished in POM (Particulate Organic Matter, i.e. phytoplankton) and CDOM (dissolved) each showing characteristic fluorescence signatures. The inorganic matter dispersed in seawaters is mostly formed by salts and mineral detritus, which are usually non fluorescing species. Some local effects, e.g. bubbles, foam, waves etc., that may affect the received signal intensity must be taken into account during the fluorosensor lidar data analysis.

In the following, we recall the relevant relations used for analysing the range resolved lidar profiles. A linear regime for the laser excitation and low chromophore densities are assumed for all the species present in natural (unpolluted) offshore seawater, so that saturation can be neglected. Moreover, for the present experimental apparatus, described in more detail in the next section, a single scattering model is appropriate also in the case of relatively turbid water (11). A simplified version of the lidar equation will be considered, which in the case of Raman scattering reads:

$$P_D^R(I_R, R) = P_l \frac{A_0}{4pR^2} \mathbf{x}(I) N_W \sigma_W(R) e^{-\int_0^R k_T(R') dR'} \frac{1}{k_T(R)} [1 - e^{-k_T DR}] \mathbf{h}(R) \quad (1)$$

where P_D , P_l are the received and transmitted powers for a laser pulse of duration $t_l = 2nDR/c$, A_0/R^2 is the acceptance solid angle of the receiver optics, $\mathbf{x}(I)$ is the receiver's spectral transmission factor, $N_W \sigma_W$ is the water number density times the Raman cross section, $k_T(R) = k(I_l, R) + k(I_R, R)$ is the total extinction coefficient at the laser (l) and Raman (R) wavelength, and $\mathbf{h}(R)$ is the receiver optics collection efficiency, describing how the laser echo enters into the detector sensitive area. The fluorescent emission from excited molecules, has a form similar to equation(1):

$$P_D^F(I, R) = P_l \frac{A_0}{4pR^2} \frac{\mathbf{s}^A(I_l) F(I_l, I) K_0(I) I_l}{I} N_0(R) e^{-\int_0^R k'_T(R') dR'} \frac{1}{k'_T(R)} (1 - e^{-k'_T DR}) \mathbf{h}(R) \quad (2)$$

where $k'_T(R) = k(I_l, R) + k(I, R)$ is the total extinction coefficient at the laser I_l and fluorescent I wavelength, $\mathbf{s}^A(I_l)$ is the absorption cross section, F is the fluorescence yield, $K_0(I)$ is an effective spectral filter efficiency, having defined the remaining terms as in equation(1). Retrieval of chromophores density N_0 along the water column, represents a very complex task since inversion of equations(1) and (2) is not straightforward, because such density appears not only as a factor but also in the extinction term, whose functional form is not linear and empirically defined only in some special cases. Several papers have appeared dealing with this complicated matter (see (12) and references), demonstrating that under additional simplifying hypothesis of homogeneous water column, and assuming fluorescence lifetimes for all the fluorophores significantly shorter than both the laser pulsewidth and the detector time response, it is possible to obtain the range resolved two path extinction coefficient, written as:

$$k(I_l) + k(I) = -\frac{d}{dR} \ln \left[\frac{P_D(R) R^2}{\mathbf{h}(R)} \right] \quad (3)$$

A simultaneous evaluation of equation(3) for a number of different spectral channels, including the elastic one, allows for determining the extinction coefficient at each selected wavelength.

METHODS

Installing the range resolved lidar fluorosensor on the bottom of the ship (Figure 2), to better investigate subsurface seawater layers and both to reduce the sun light background and to enhance the detection limit for signals coming from the water mass, was not a minor technological problem to solve. The afterhold n° 4 of the R/V *Italica*, was chosen due to its central position and to the good chances of a direct connection between the electronics and the mobile lidar laboratory on the upper deck.

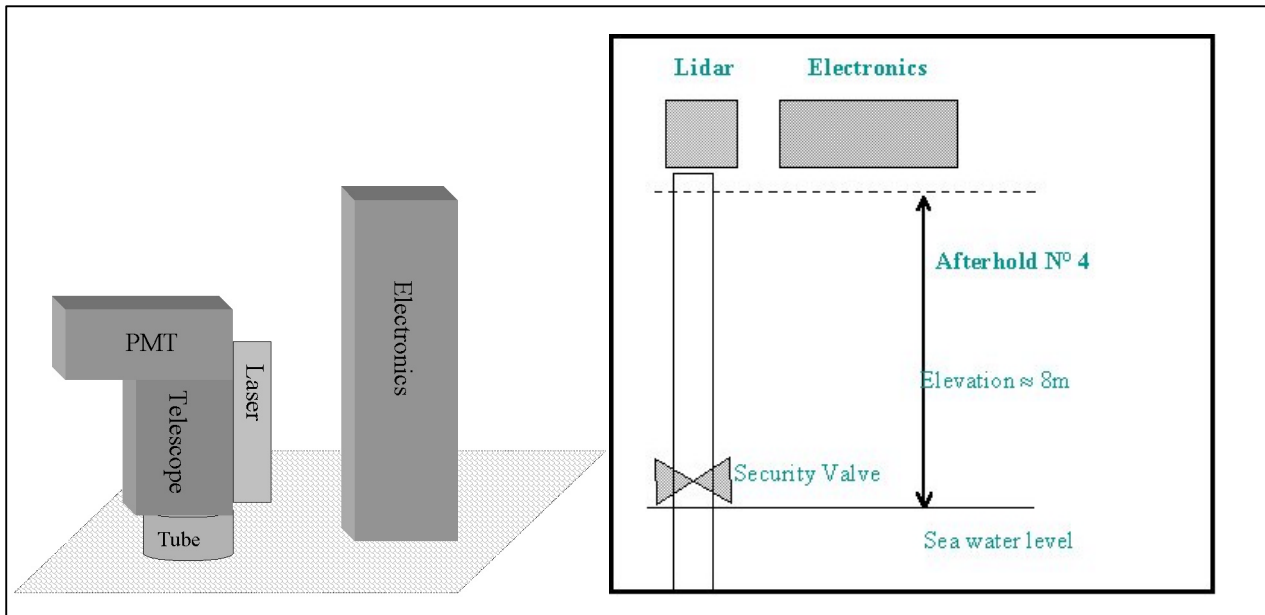


Figure 2: Sketch of the ship bottom installation of the range resolved lidar fluorosensor.

In the final arrangement, the laser beam reaches deep waters through a large size tube (10 m long, 400 mm dia., 8 mm thick), equipped with a 500 mm valve and connected on top to the optical system via a sealed Plexiglas window. This optical connection also allows to inflate compressed air inside the tube in order to lower the seawater level. The lidar fluorosensor body is kept about 8 m above the inner water, corresponding to 2 m above the floating line of the ship. The electronics, required for control and data acquisition, are located nearby the lidar main body. The detailed characteristics of the apparatus are summarised in Table 1. The range resolved lidar is similar to the surface one (13), a part from the limitation to only 4 detection channels at 355, 403, 450 and 680nm). For each channel, the complete time profile of the echo is recorded, as collected from the crossed marine layers, by means of a digital scope (LeCroy Mod. 9354C) operating at 500 Msamples/s with 8-bit for amplitude resolution. In order to increase the SNR, an average on some hundred of laser shots has been performed, resulting in an increase of the 8 bit amplitude resolution of the transient digitiser, to an effective value of 11-12 bit. The acquired data are then transmitted *on line* via Ethernet from the embedded VME to the PC, to the main computer for elaboration.

In the off-line data processing, the atmospheric extinction has been neglected, due to the short distance crossed by the radiation, while several sources of errors have been observed to affect the final measurements. Random irregularities of the air-water interface, because of the ship motion induced turbulence, produced intense signal fluctuations. This effect has been taken into consideration by adding an appropriate filter in the post-processing software. Also large increases of concentration of fluorescent matter, causing an increase in turbidity and a consequent decrease of Raman signal should be considered among the error sources, especially for its effect upon signal normalization. After considering the main potential error sources, the accuracy of the data presented here should be

within 10% -15 %. Range resolved data have been computed from the return signals and, after time integration, have been compared to the simultaneous findings of the surface lidar.

Table 1. Main characteristics of the lidar fluorosensor components

<i>Transmitter</i>	Nd:YAG laser	@ 355 nm
	Energy	30 mJ
	Pulse length	10 ns
	Ppr	10 Hz
<i>Expander</i>	Variable	3x
<i>Detectors</i>	Hamamatsu PMT	R928 (2), R1744 (2)
<i>Filters</i>	Dichroic	T>90% (@ 400 nm)
	Interference	355, 402, 450, 680 nm
<i>Telescope</i>	Cassegrain	38 cm dia. F#2
<i>Fiber Optic</i>	Plastic Multifiber	four Branches
	Bundle Diameter	Input 24.5 mm, Output 7 mm
	Length	50 cm
<i>Digitizer</i>	LeCroy 9354C oscilloscope	four channels, 500 Ms/s, 8 bit
<i>Computer</i>	VME-CPU embedded	Pentium II 266MHz

During the present campaign the lidar and the lamp spectrofluorometer were also operated as part of the instrumentation installed in the mobile fluorosensor laboratory. The lidar fluorosensor apparatus adopts a similar technical design in its components to the ship bottom set up apart from the range integrated signal acquisition, thus resulting in superficial monitoring capability. The spectrofluorometer (PTI Quantamaster) allows for multispectral analysis of the crossed waters, at different UV excitation wavelengths, on local samples for calibration purposes.

RESULTS

The Range Resolved (RR) lidar has been mounted on the R/V *Italica* in October 1999, before leaving for the Antarctic mission, together with the mobile fluorosensor laboratory including the lidar fluorosensor, for surface monitoring and the spectrofluorometer, for local determinations. All the apparatus were operated in the Ross Sea during the XV Italian Campaign. The optical and electronic settings of the RR LIF apparatus, as optimised before leaving the Italian harbour of Manfredonia, had to be changed in order to match the optical characteristics of the Antarctic seawaters. The telescope field of view and the beam expander parameters have been modified in order to avoid PMT saturation and to maximise the received signals at the reached depth. Time resolved profiles at three simultaneously acquired different channels (Raman, CDOM and Chl-a fluorescence) are shown in Figure 3. The theoretical curves straddling experimental points of Figure 3, are obtained by equations (1) and (2) using the literature parameters of Table 2 for the total extinction. The difference in the maximum depth is due to corresponding differences in the optical attenuations for each received signal, remarkably lower for the blue channel than for the red one.

It is also interesting to observe in Figure 3, the nearly four orders of magnitude amplitude dynamics of lidar signals, meaning that the experimental system is actually performing at the best of its possibilities. If a greater depth is needed, then it is necessary to increase the geometrical compression, to extend the signal dynamic, or to assemble the lidar system as a submersible unit (16).

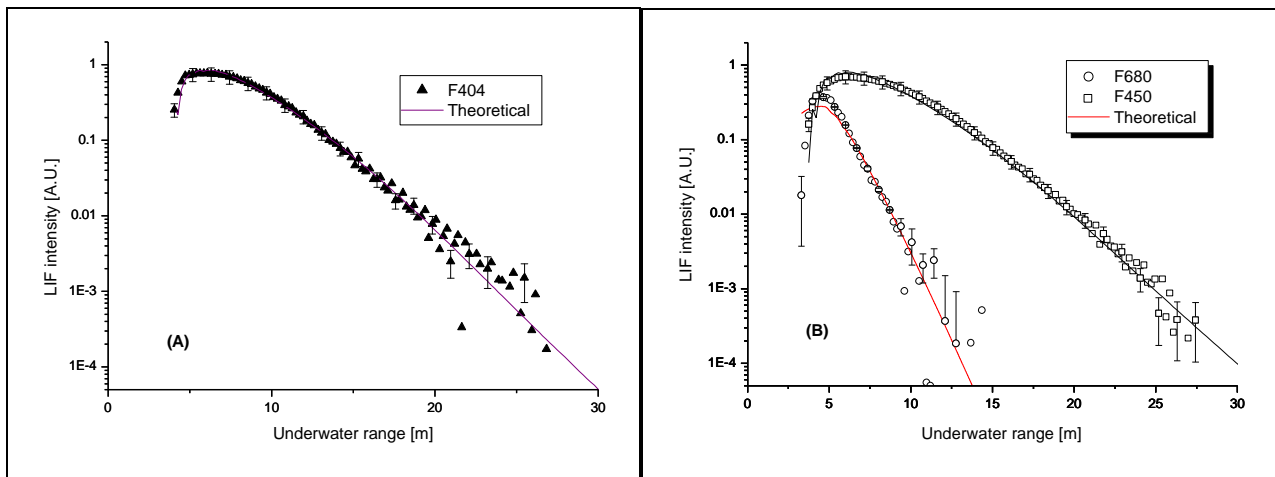


Figure 3: Range resolved LIF signal as measured with the ship vessel apparatus: a) Raman signal; b) CDOM and Chl-a fluorescence emission. Antarctic Ross sea, Date UTC: 21:30 02/02/2000.

Table 2. Total extinction coefficients used in theoretical lidar profiles (case I water) (14, 15)

Wavelength [nm]	k_T [m^{-1}]
355	$2.4 \cdot 10^{-1}$
404	$5.8 \cdot 10^{-2}$
450	$2.8 \cdot 10^{-2}$
680	$4.2 \cdot 10^{-1}$

An intercomparison between the RR and integrated lidars, simultaneously operated, and a local spectrofluorometer has been performed during the Antarctic campaign. In this test, the RR LIF signals have been time integrated in order to obtain an average information along the water column investigated. In Figure 4, the Chl-a fluorescence emission at 680 nm, continuously monitored during three days of measurements, show a trend in agreement as measured both by the surface and subsurface lidars, and by the local spectrofluorometer, respectively, although some differences are observed. Possible causes of the mismatching among the different systems, are related to various physical and instrumental effects, including a lower laser energy for the external lidar, a different space extension of the integration cell ranging from few cm, for the local spectrofluorometric determinations to some metres for the remote sensed measurement, to ship shadowing effects, and to a minor extent to the current environmental conditions (superficial waves or foams, albedo at the seawater surface).

The daily cycle observed in Chl-a fluorescence emission, can deal with the natural Phytoplankton photosynthetic activity, floating in the lower layers, and not to the possible contribution of the background solar radiation, since it appears as well in the ship-bottom column which is more efficiently screened from the available sunlight.

Total RR extinction profiles have been retrieved by using equation (3), at the different channels of laser, water Raman, CDOM and Chl-a fluorescence emissions. Daily sets of measurements, for the laser and channels at 450nm, 404nm, and 680nm, are shown in Figures 5, 6 and 7, as sampled on 3/02/00. The vertical axis, in metres, starts from the actual sea level at the ship keel (-5m).

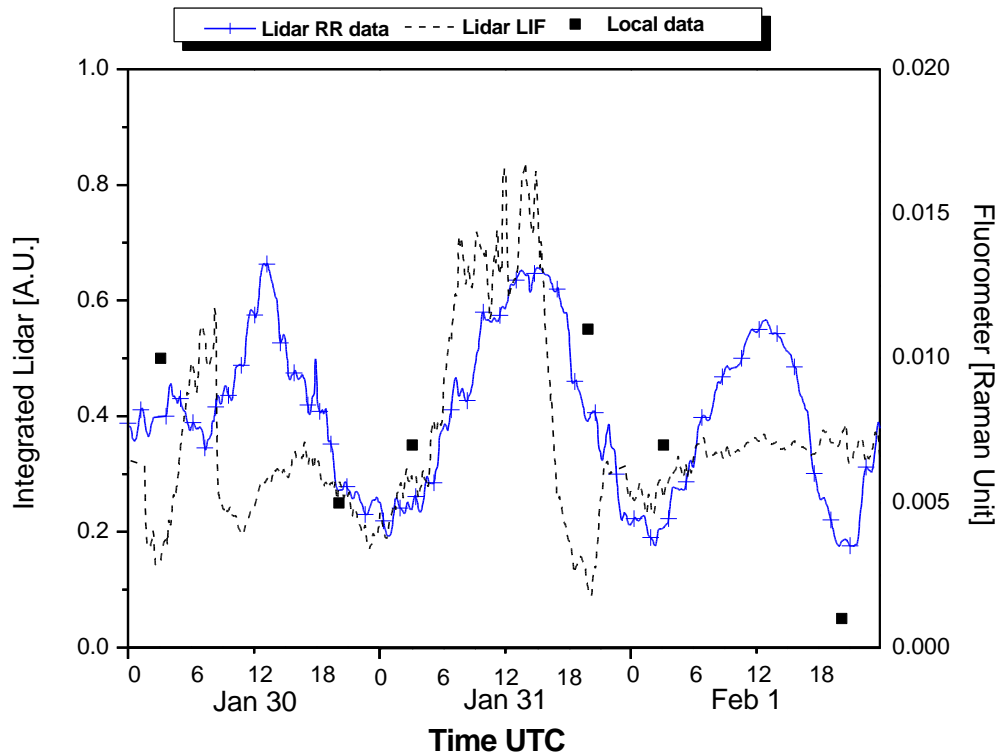


Figure 4: Comparison of integrated lidar signals collected with the surface system (dashed line) with the range resolved one (continuous line) and the fluorescence data obtained from local sampling (square data points) are also reported. Please note, in the southern hemisphere the highest sun elevation is at 0:00 UTC.

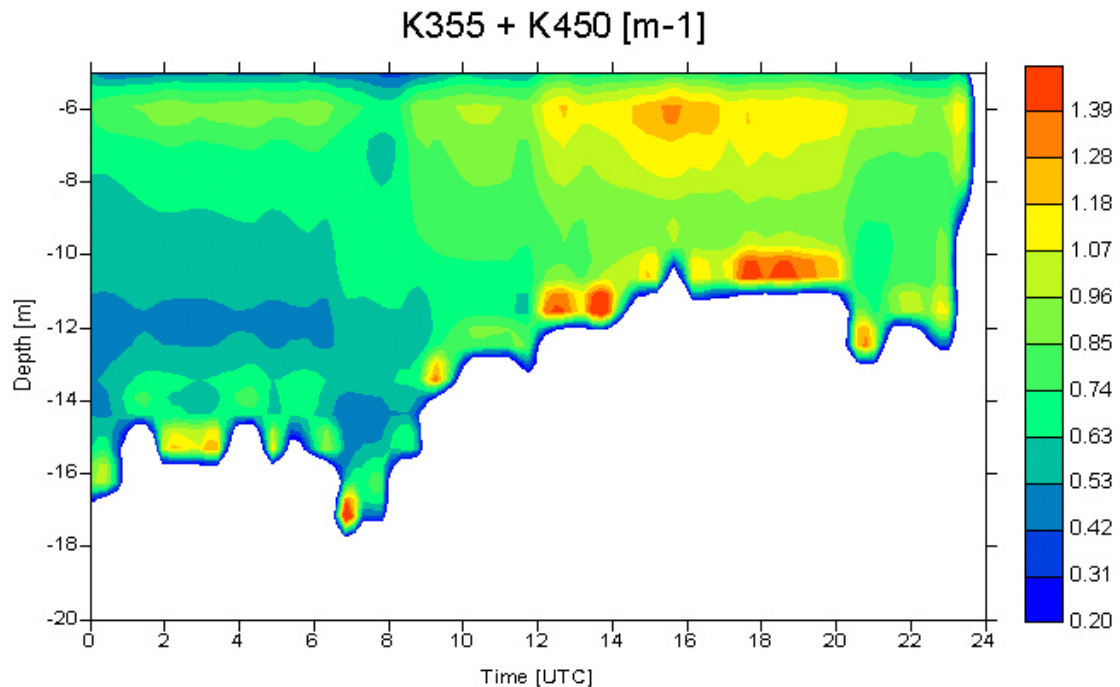


Figure 5: Range resolved total extinction profile, for the excitation @ $\lambda=355\text{nm}$ and emission @ $\lambda=450\text{nm}$. [Antarctic Ross sea, Feb. 03 2000].

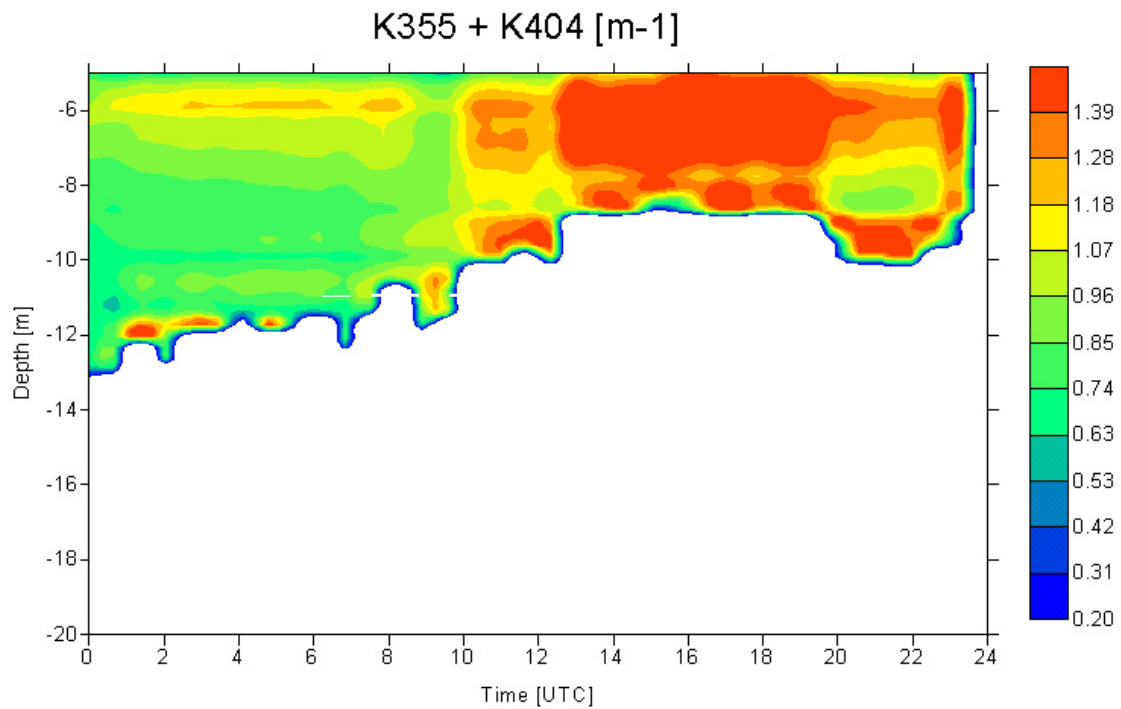


Figure 6: Range resolved total extinction profile, for the excitation @ $\lambda=355\text{nm}$ and emission @ $\lambda=402\text{nm}$. [Antarctic Ross sea, Feb. 03 2000].

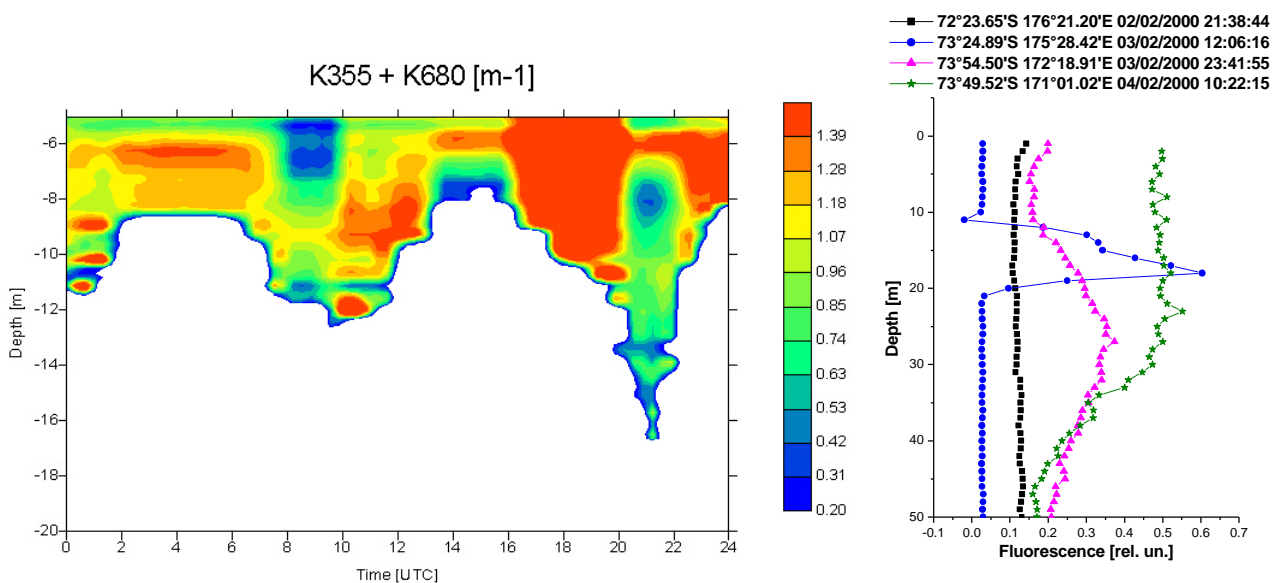


Figure 7: Range resolved total extinction profile, for the excitation @ $\lambda=355\text{nm}$ and emission @ $\lambda=680\text{nm}$, and corresponding CTD vertical fluorescence profiles (UTC time and geographical positions are indicated in the figure). [Antarctic Ross sea, Feb. 03 2000].

The distributions, reported in the last three figures, differ in their maximal depths reached, mainly due to the optical seawater characteristics. Measured distributions are also influenced by the ship motion causing turbulence and a large number of bubbles within the field of view of the detector. The profiles of Figure 5, including laser and CDOM total extinction, cover a larger submarine area with respect to corresponding channels at Raman and Chlorophyll signals. In this figure, a clear indication of a stratified layer at 6-7 m is observed, in coincidence to the chlorophyll fluorescence (Figure 7) at the same hours, thus suggesting a contribution of phytoplankton accessory pigments to the CDOM fluorescence emission in the layer. These two layers increase their intensities in the late

hours (16-18). This effect, particularly for the red fluorescence channel, is in agreement with the daily behaviour already observed the day preceding and presented in Figure 4. A clear indication of chlorophyll's shifts are also observed in the concurrent CTD fluorometer (SeaTech inc.) in the up-cast operation of the rosette, where layers of fluorescence phytoplankton are observed moving from the surface down to 30m. It has to be pointed out that CDOM fluorescence emission is significantly higher with respect to superficial layer (two - five times more), already measured during previous monitoring campaign in the same area (13), due to the superficial formation of thin fluorescent layers over the seawater surface.

CONCLUSIONS

The lidar fluorosensor for remote monitoring of marine ecosystems has already fully demonstrated its capabilities in producing thematic maps of different fluorescence pigments characteristic of phytoplankton population and of seawater parameters (CDOM and turbidity). The information obtained from surface distributions, which may be linked to satellite images, can be extended to subsurface layers by exploiting the new generation of range resolved systems designed for this purpose. The new apparatus for range resolved measurements, has found its specific application in monitoring vertical concentration profiles of dissolved organic substances and phytoplankton, from the ship bottom and for several tens of metres deeper along a water column, for clear waters. Time resolved operation at each collected signal, corresponding to a depth profile measurement on the relevant channel, is the main innovative feature of this apparatus. Information on the stratification of fluorescent substances is gained. Namely surface and subsurface distributions for chlorophyll appear basically in agreement, whereas large discrepancies are observed on the CDOM channel which dominates the emission collected at the surface.

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