Italian National Agency for New Technologies, Energy and Sustainable Economic Development

Environmental monitoring by laser radar

Luca Fiorani, **Francesco Colao, Antonio Palucci**

Laser Applications Section, ENEA, Italy

3rd Workshop on Optoelectronic Techniques and Environmental Monitoring

OTEM 2009 WORKSHOP

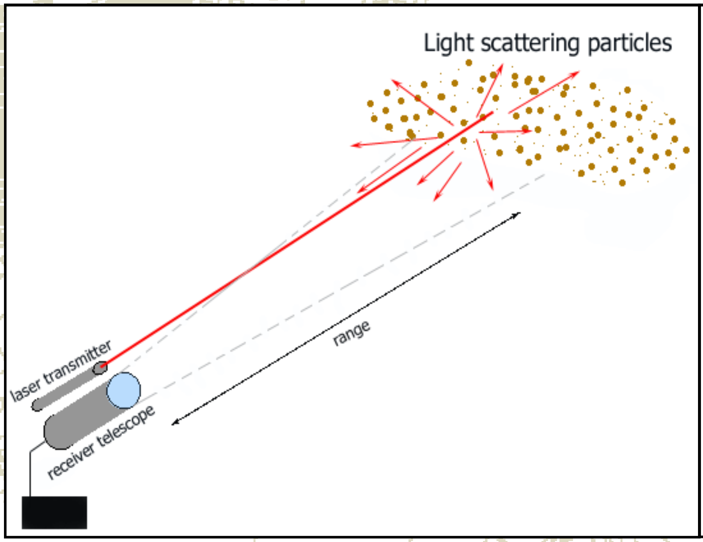
Romania, Bucharest
September 30 - October 2

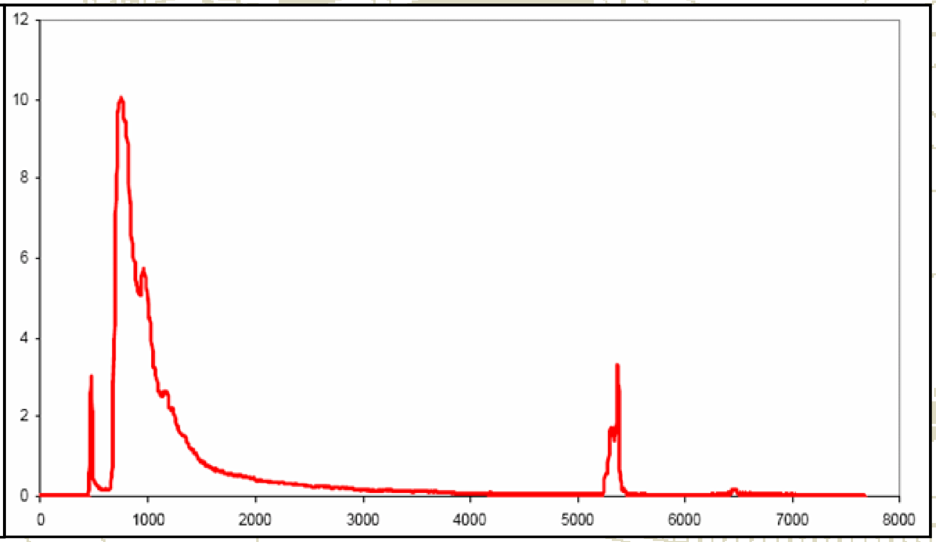
Plan

- Laser radar (atmospheric case)
  - monitoring of industrial zones (absorption)
  - profiling of volcanic plumes (backscattering & absorption)
- Laser radar (hydrographic case)
  - characterization of sea waters (fluorescence)
- Conclusions

Atmospheric lidar

- Lidar (light detection and ranging) = laser radar
- A laser sends a light pulse to the atmosphere
- The atmosphere interacts with the laser beam
- A telescope detects the backscattered light
- R=ct/2





Advantages of lidar

- Continuous retrieval of aerosol load, wind speed and gas concentration profile in a considerable range and with a good spatio-temporal resolution
- Probe-less measurement, thus eliminating the possibility of modifying the sample
- Integrated-path determination, less sensitive to local effects
- Capability of sweeping the complete hemisphere, thus allowing to follow the physico-chemical dynamics of the atmosphere

Backscattering lidar

- **Lidar equation**

$$n(R,\lambda)=n_0(\lambda)\ (A/R^2)\ \zeta(\lambda)\ \beta(R,\lambda)\ (c\tau_D/2)\ \exp[-2\int_0^R \alpha(R',\lambda)dR']$$

n (n_0) number of detected photons (transmitted)

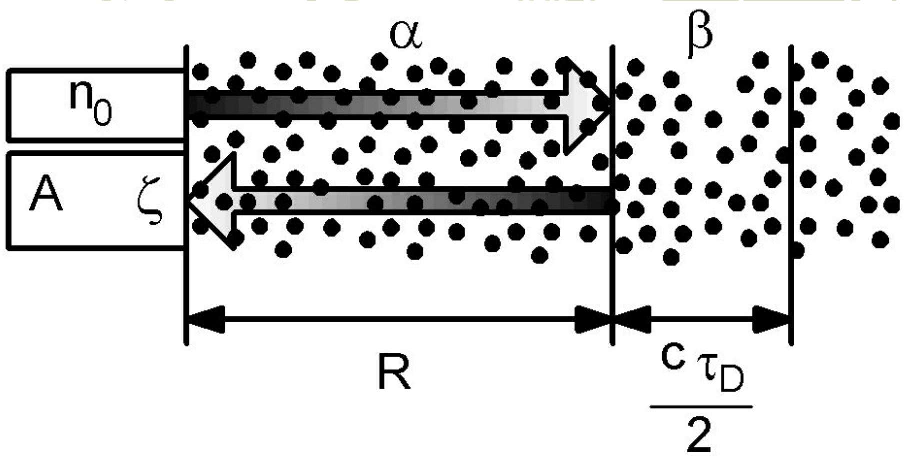
$R=ct/2$ is the range (c is the speed of light, t is the time between transmission and detection)

λ is the wavelength

A (ζ) is the detection surface (efficiency)

β (α) is the backscattering (extinction) coefficient

τ_D is the response time of the detector



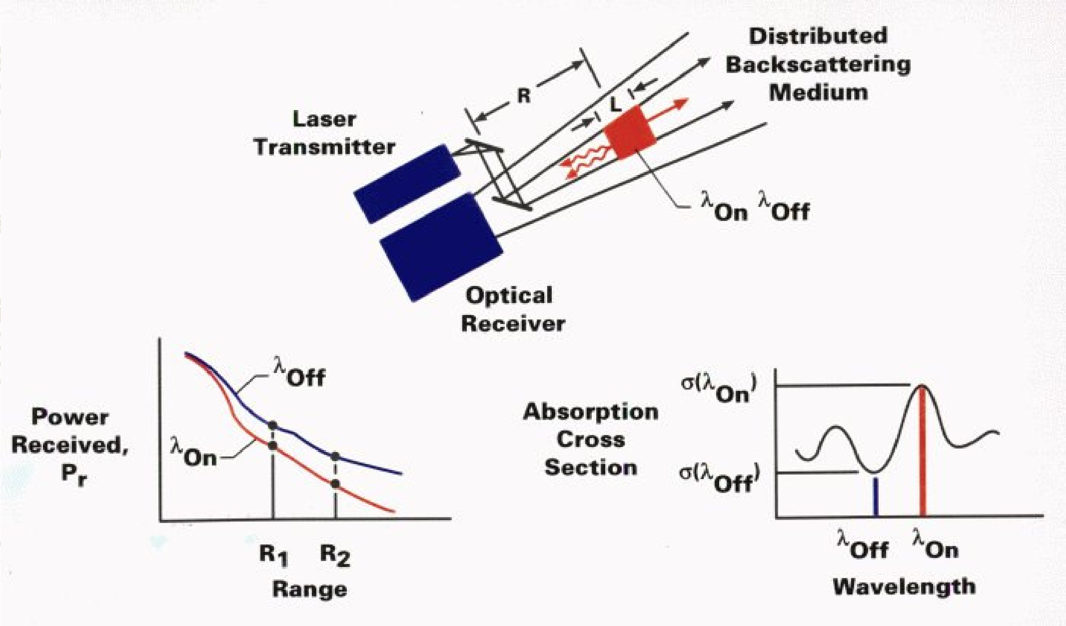
Differential absorption lidar

- **DIAL (differential absorption lidar) equation**

$$C(R)=\{1/[2(\sigma_{ON}-\sigma_{OFF})]\}(d/dR)\ln[n(R,\lambda_{OFF})/n(R,\lambda_{ON})]$$

σ_{ON} (σ_{OFF}) is the cross section of the molecule at λ_{ON} (λ_{OFF})

λ_{ON} (λ_{OFF}) is the more (less) absorbed wavelength



Lidar at Frascati

- **From the fixed lab… to the mobile lab**

ENEA lidar ground station in the eighties.

ENVILAB (ENVIronmental LABoratory).

ATLAS

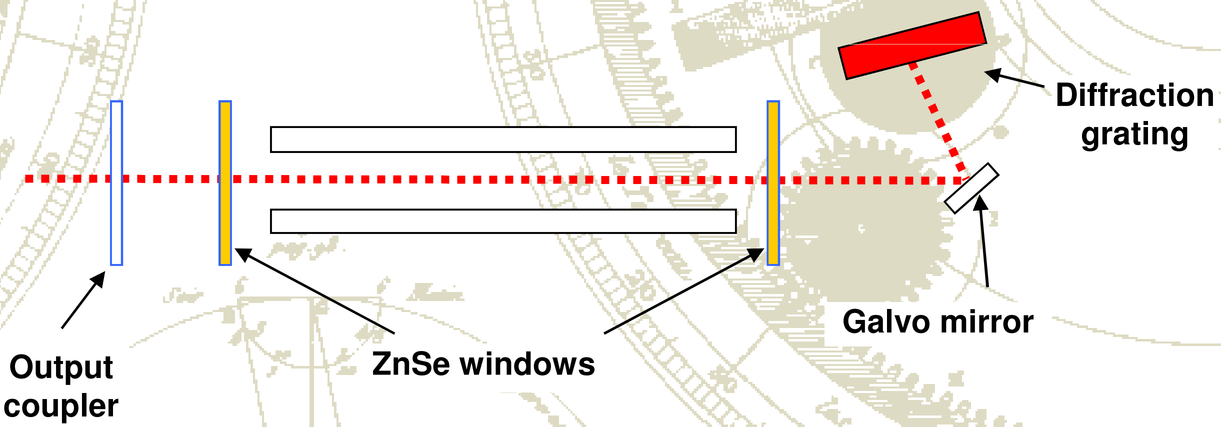
- **ATLAS** (**a**gile **t**uner **l**idar for **a**tmospheric **s**ensing)

ATLAS (Agile Tuner Lidar for Atmospheric Sensing). Bottom-left: CO_2 laser. Right: Newton telescope. Top-left: control/acquisition computer.

ATLAS

- The agile tuner allows the tunability of the laser and, as a consequence, the detection of:
  - Ammonia
  - Ethylene
  - Ozone
  - Water vapor

  ...



ATLAS

- **Specifications**

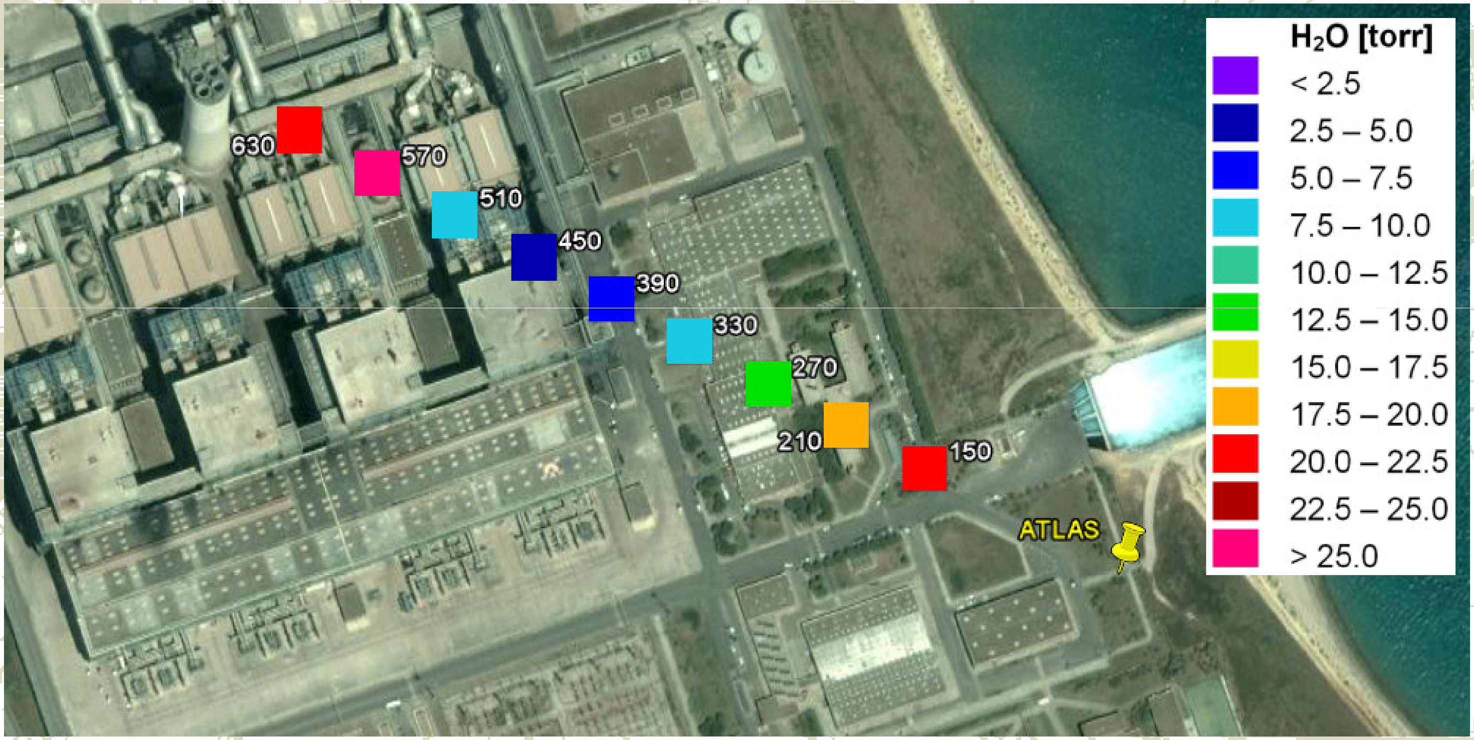
Transmitter	Pulse energy	850 mJ (at the 10P20 emission line)
	Pulse duration	60 ns (full width at half maximum)
	Repetition rate	1 ÷ 20 Hz
	Transmitted wavelength	9.2 ÷ 10.8 μm
	Beam divergence	0.7 mrad
Receiver	Mirror coating	Au
	Diameter	310 mm
	Focal length	1.2 m
Detector	Diameter	1 mm
	Specific detectivity	4×10^{10} cm $Hz^{1/2}$ W^{-1}
	Gain	200
	Linear dynamic range	0.1 ÷ 1000 mV
	Bandwidth	0 ÷ 10 MHz
Analog-to-digital converter	Dynamic range	8 bit
	Sampling rate	10 Ms s^{-1}

Monitoring application

- **Power Plant of Cerano (Brindisi)**

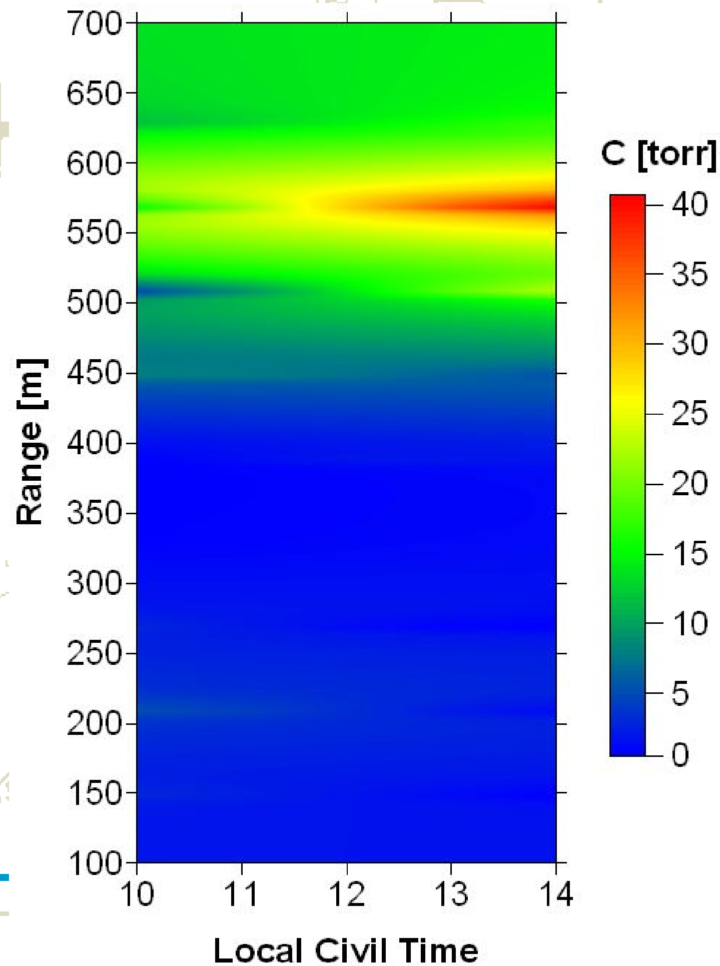
Monitoring application

- **Concentration profiles in industrial zones**



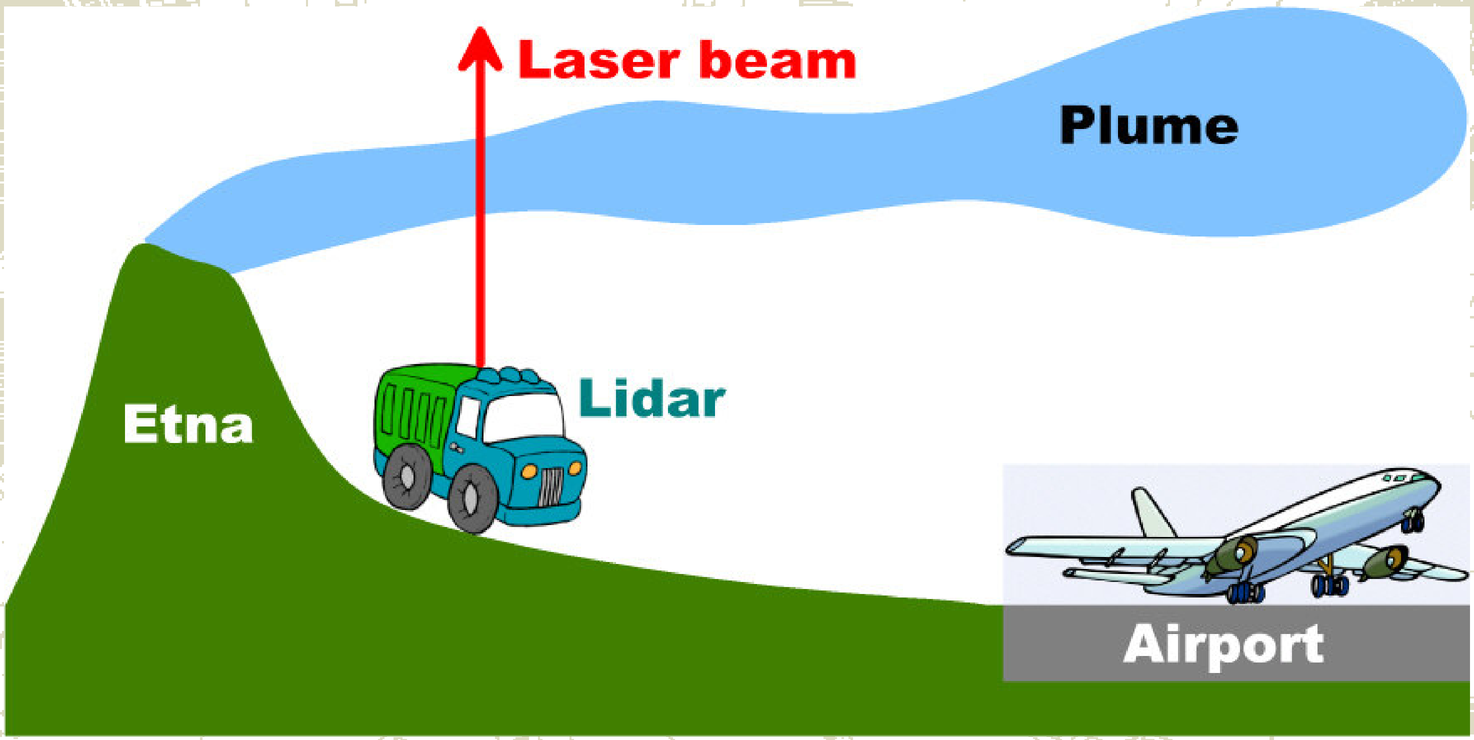
Monitoring application

- **Spatiotemporal evolution**



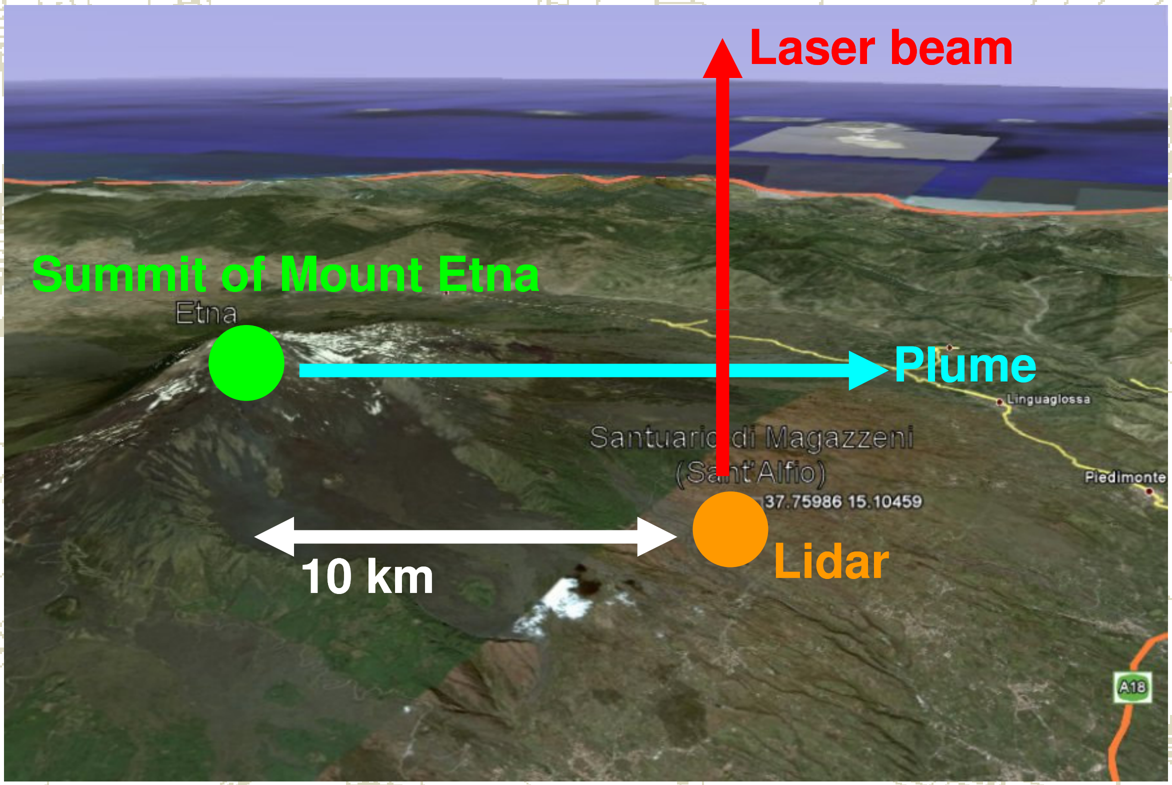
Plume profiling

- **Experimental scheme**



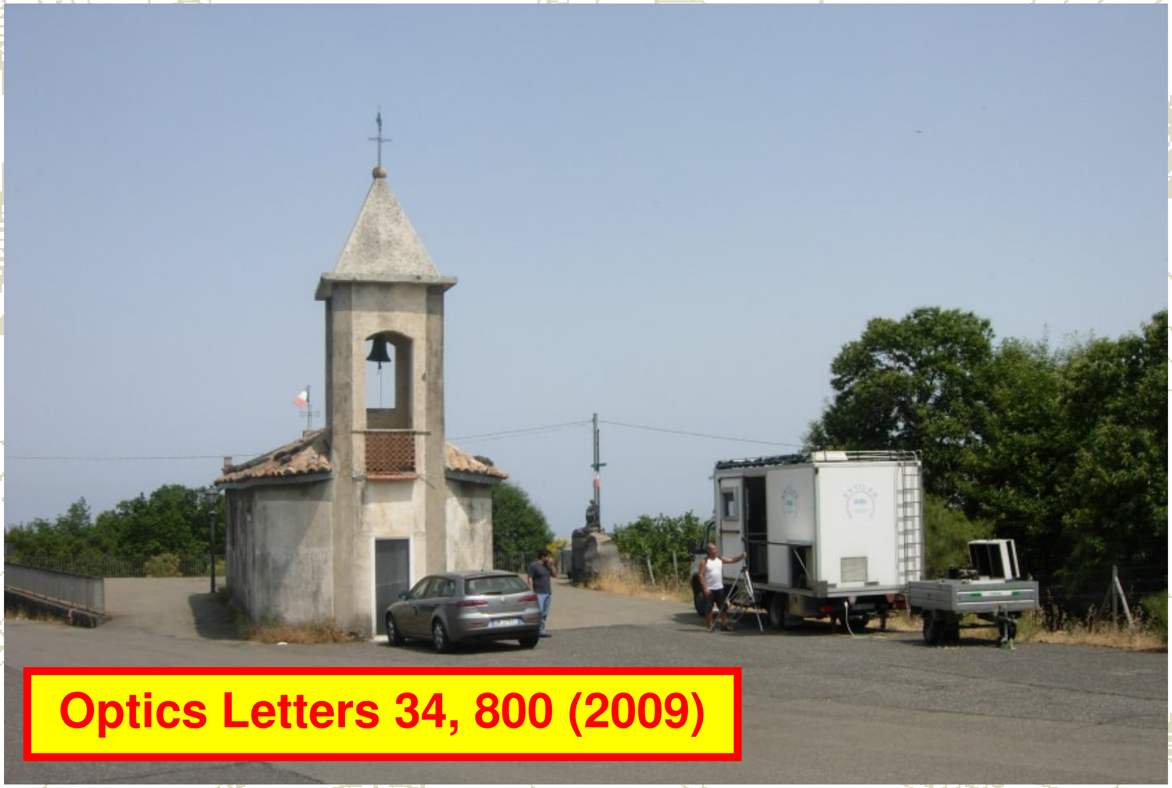
Plume profiling

- **Geographical situation**



Plume profiling

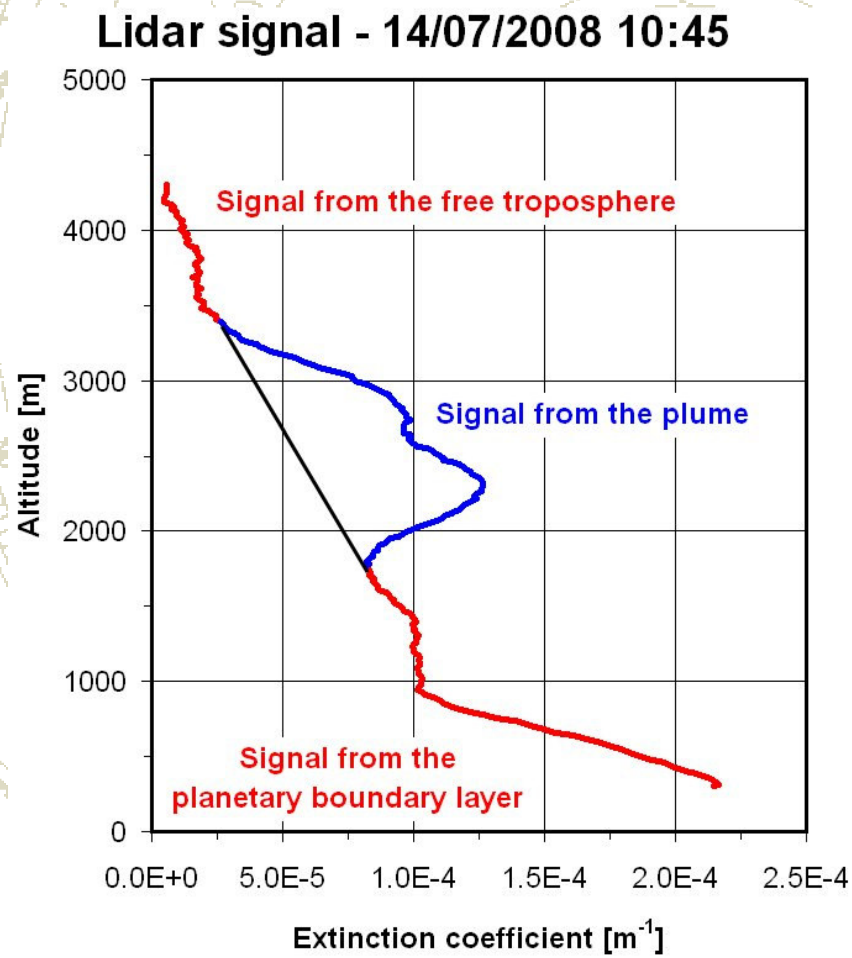
- Sant'Alfio (Catania) – Santuario Magazzeni



Optics Letters 34, 800 (2009)

Plume profiling

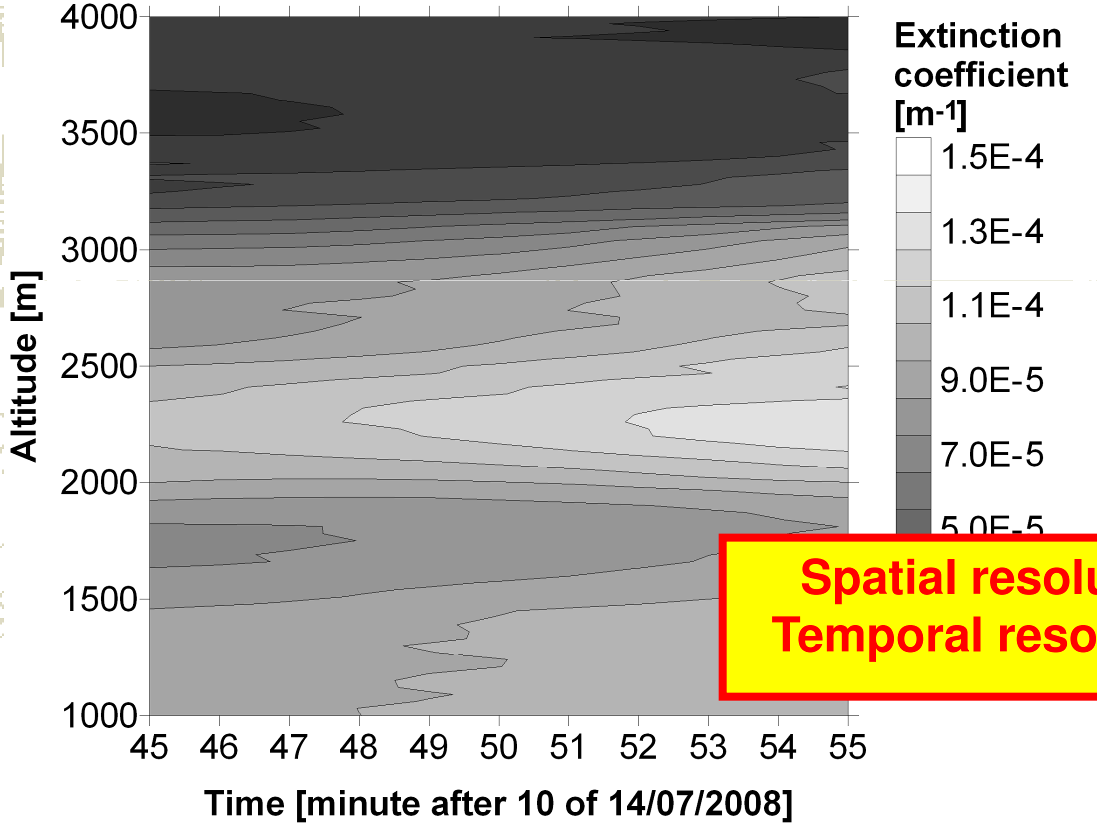
- **Extinction coefficient** calculated at 10.6 µm with an algorithm similar to those by JD Klett, Applied Optics 20 (1981) 211 and FG Fernald, Applied Optics 23 (1984) 652



Maximum range > 5 km

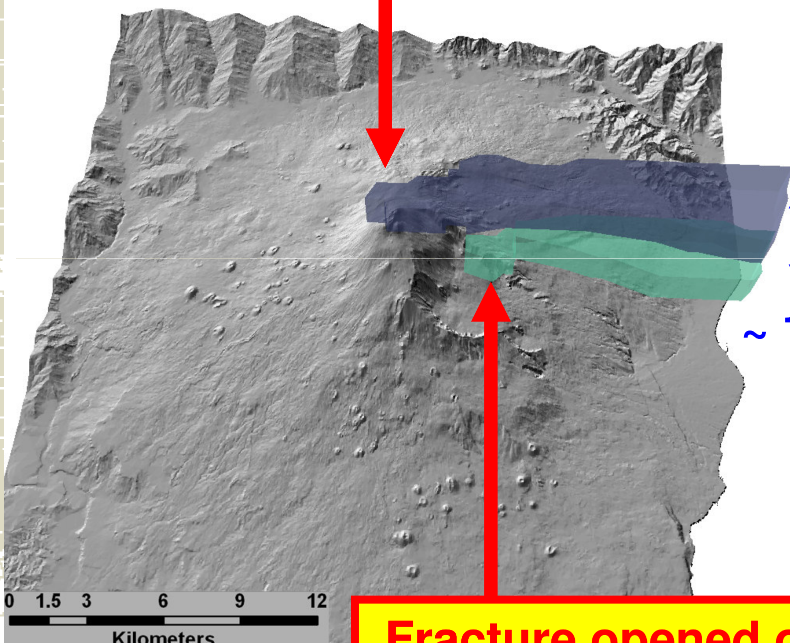
Plume profiling

- **Spatiotemporal evolution**



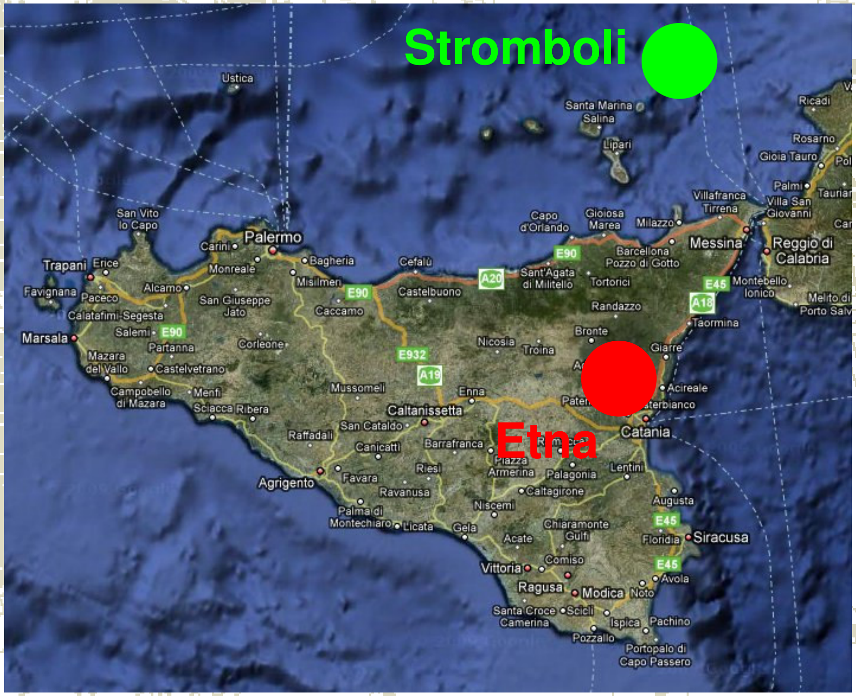
Spatial resolution: 15 m,
Temporal resolution: 1 min

Plume profiling



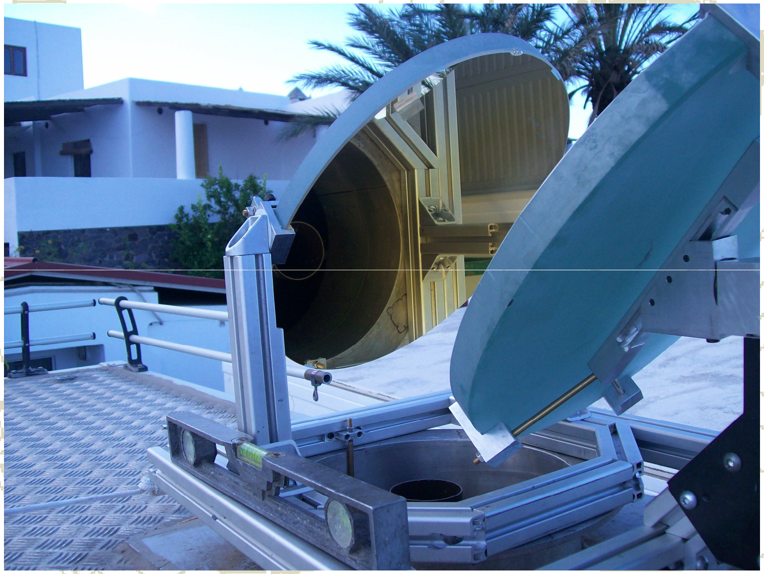
- Combining the AOT (Aerosol Optical Thickness) map (satellite) and the altitude information (lidar), two different plumes can be distinguished (thanks to MF Buongiorno, L Guerrieri, C Spinetti)

From Etna to Stromboli…



From Etna to Stromboli…

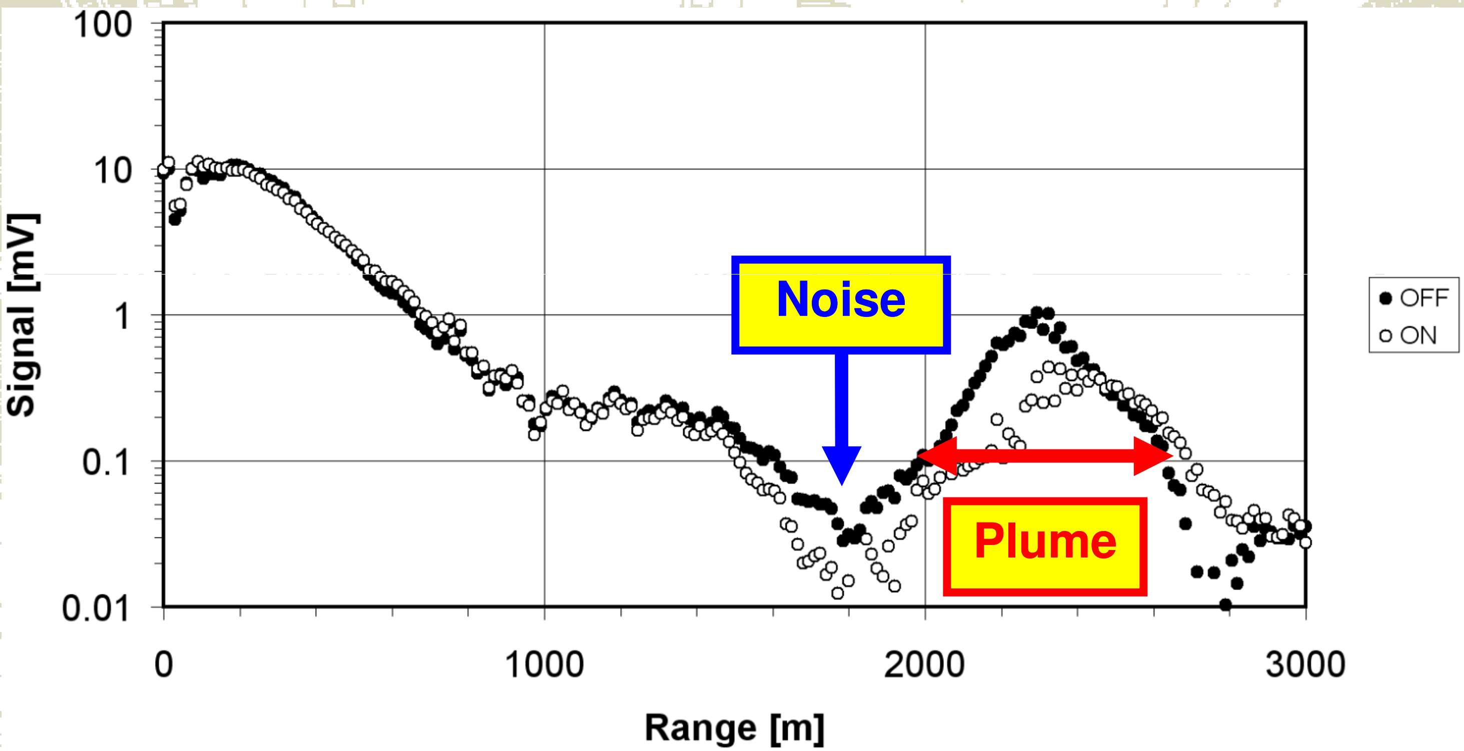
- The lidar is directed to the plume with a coelostat



12-17 September 2009

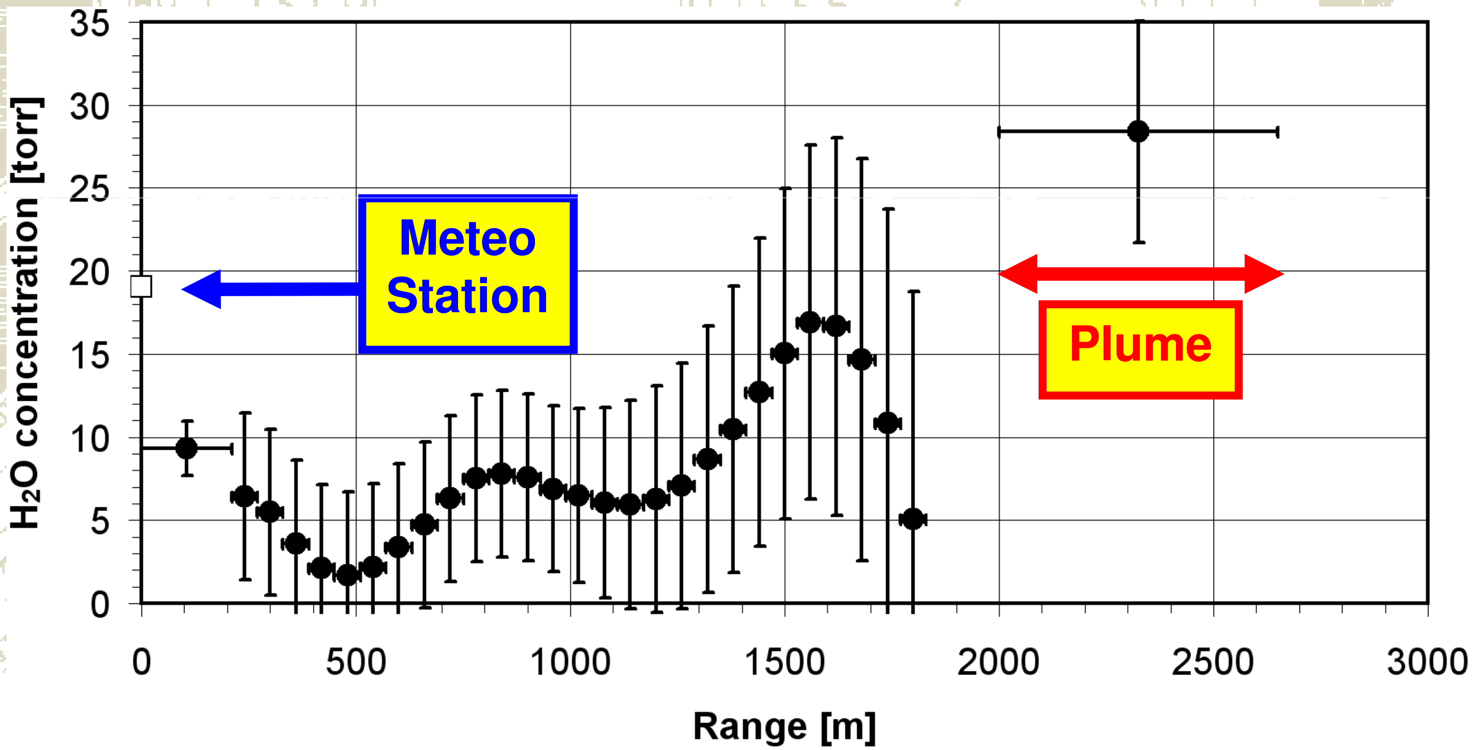
From Etna to Stromboli…

- **Lidar signals**



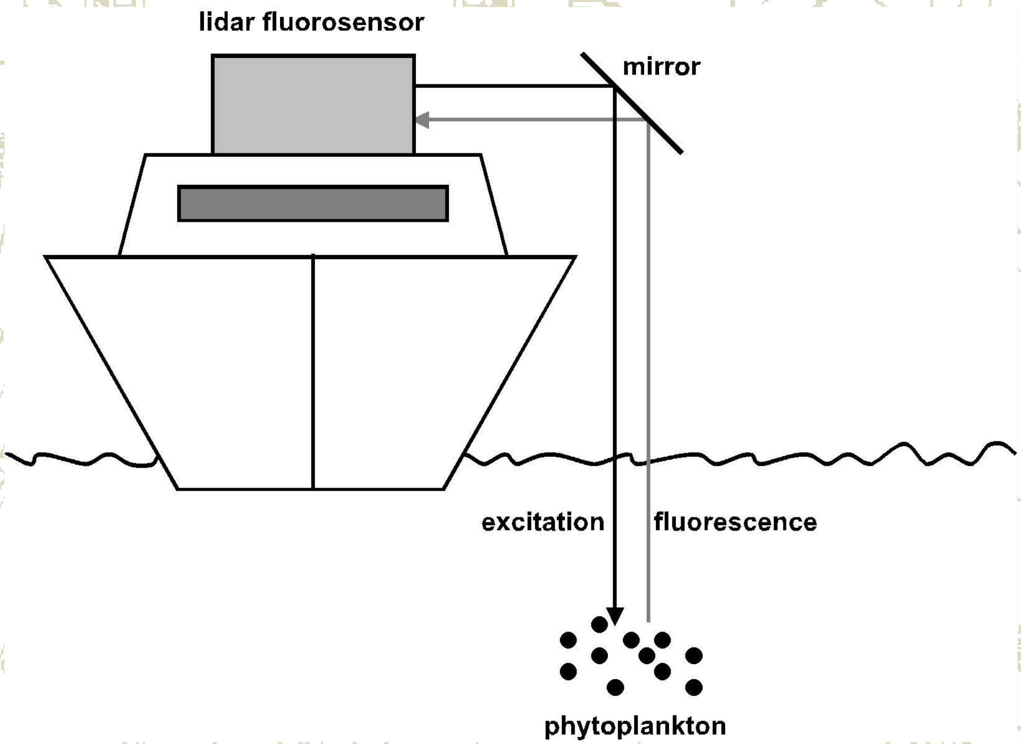
From Etna to Stromboli…

- **Water vapor concentration (preliminary)**



Lidar fluorosensor

- **Fluorosensor: laser-induced fluorescence (LIF)**



Lidar fluorosensor

- **Received energy (fluorescence)**

$$E_F(\lambda_F, R) = E_0 \frac{k_F \ A \varphi N_F(R) \sigma_F(\lambda, \lambda_F)}{R^2 \ m^2 \left[\alpha_w(\lambda) + \alpha_w(\lambda_F)\right]} \exp\{-[\alpha(\lambda) + \alpha(\lambda_F)]R_w\}$$

  - λ_F: fluorescence wavelength
  - R: range
  - E_0: transmitted energy
  - k_F:system constant
  - A: receiver area
  - φ: two-way transmission factor
  - N_F: number density of fluorescing molecules
  - σ_F: fluorescence cross section
  - λ: laser wavelength
  - α: extinction coefficient of air
  - R_w: range of water surface
  - m: refractive index of water
  - α_w: extinction coefficient of water

Lidar fluorosensor

- **Received energy (Raman scattering of water)**

$$E_R(\lambda_R, R) = E_0 \frac{k_R\, A\, \varphi\, N_R\, \sigma_R(\lambda, \lambda_R)}{R^2\, m^2\, [\alpha_w(\lambda) + \alpha_w(\lambda_R)]} \exp\{-[\alpha(\lambda) + \alpha(\lambda_R)] R_w\}$$

  - **λ_F: Raman-shifted wavelength**
  - **k_R:system constant**
  - **N_R: number density of water molecules (practically constant)**
  - **σ_R: Raman scattering cross section**

Lidar fluorosensor

- Fluorescence in Raman units

$$E^*(R) \equiv \frac{E_F(\lambda_F,R)}{E_R(\lambda_F,R)} = \frac{k_F\ N_F(R)\,\sigma_F(\lambda,\lambda_F)\left[\alpha_W(\lambda)+\alpha_W(\lambda_R)\right]\exp\{-\left[\alpha(\lambda)+\alpha(\lambda_F)\right]R_W\}}{k_R\ N_R(R)\,\sigma_R(\lambda,\lambda_R)\left[\alpha_W(\lambda)+\alpha_W(\lambda_F)\right]\exp\{-\left[\alpha(\lambda)+\alpha(\lambda_R)\right]R_W\}}$$

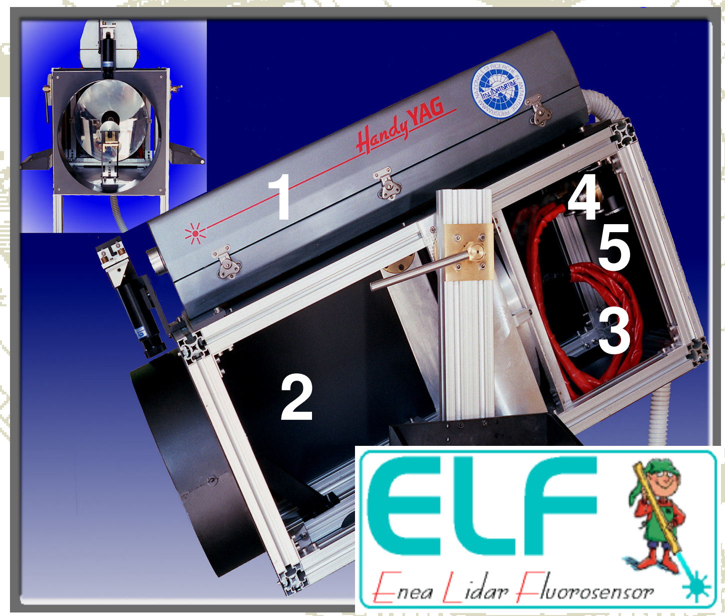
- If, as usual for CDOM (chromophoric dissolved organic matter) and chl-a (chlorophyll *a*) detection, the extinction coefficients ratio changes slowly and the exponentials ratio is close to unity, E* can be written as (k is a new system constant including also the cross sections)

$$E^*(R) = k\,\frac{N_F(R)}{N_R}$$

ELF: ENEA Lidar Fluorosensor

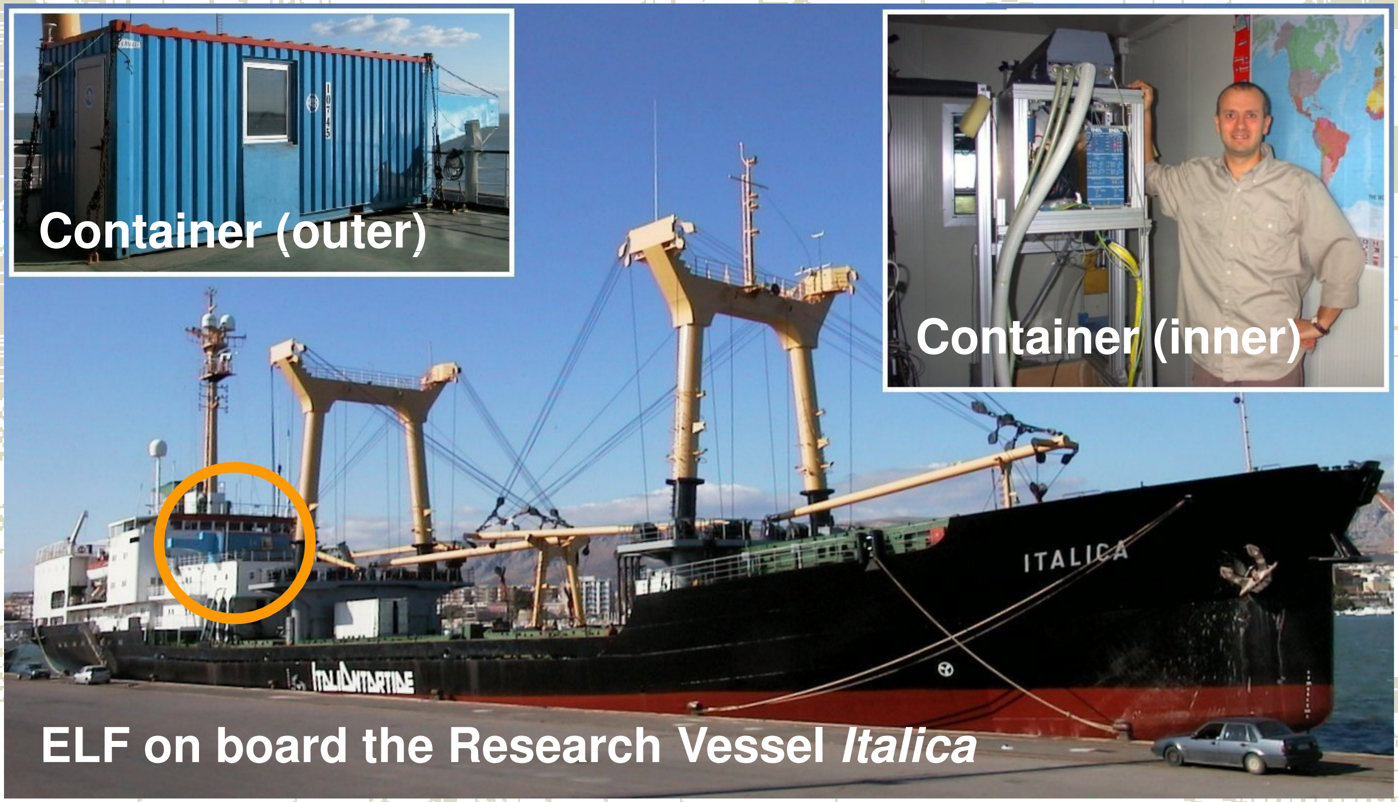
- **Transmitter:** frequency-tripled Nd:YAG laser (1)
- **Receiver:** Cassegrain telescope (2)
- **Detection:** optical fibers (3), bandpass filters (4) and photomultiplier tubes (5)

LIF Band	λ[nm]	Notes
Excitation	355	Laser
Raman sc. (H_2O)	404	Transparency Oil slick thickness LIF data normalization
CDOM fl.	450	Humic and fulvic acids Crude oils
Phycoerytrin fl.	575	Algal pigment
Phycocyanin fl.	630	Algal pigment
Chlorophyll-a fl.	680	Algal pigment



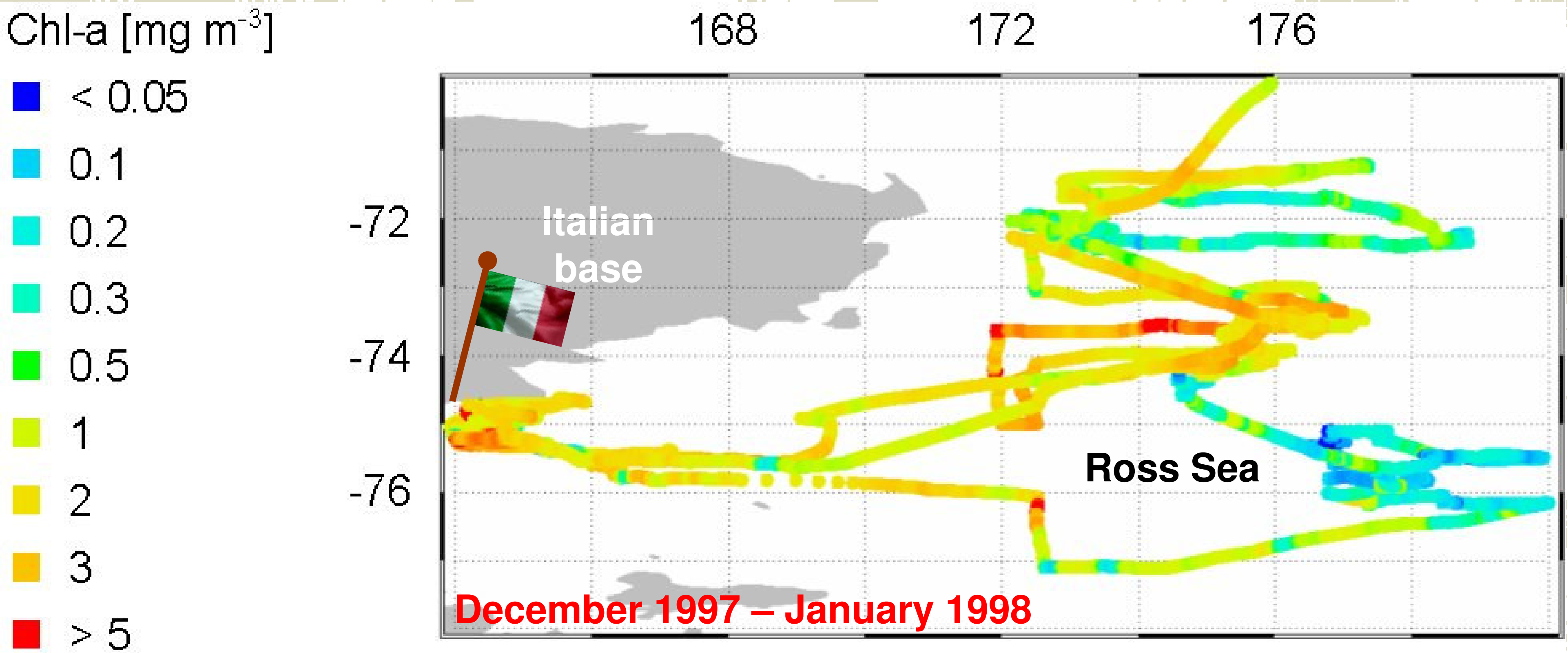
ELF oceanographic campaigns

- **5 in Antarctica, 3 in the Arctic Ocean, 2 in the Mediterranean Sea and 2 from Italy to New Zealand**



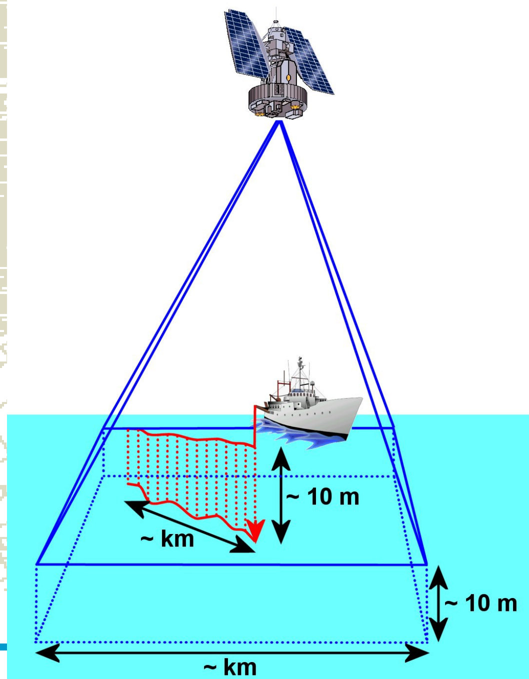
ELF thematic maps of chlorophyll-a

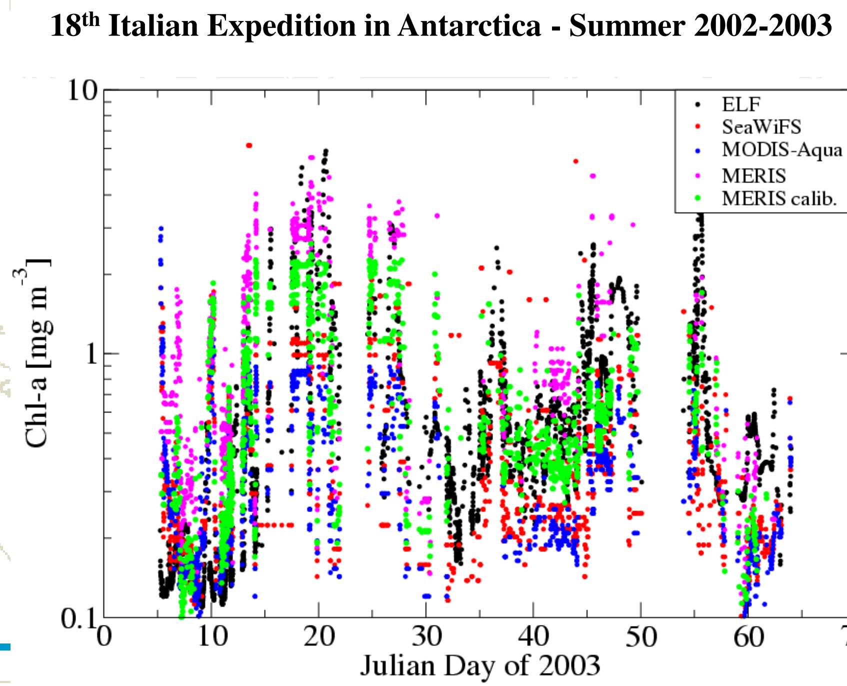
- **Lidar measurements (calibrated and georeferenced) can be compared with radiometers data**



ELF comparison with radiometers

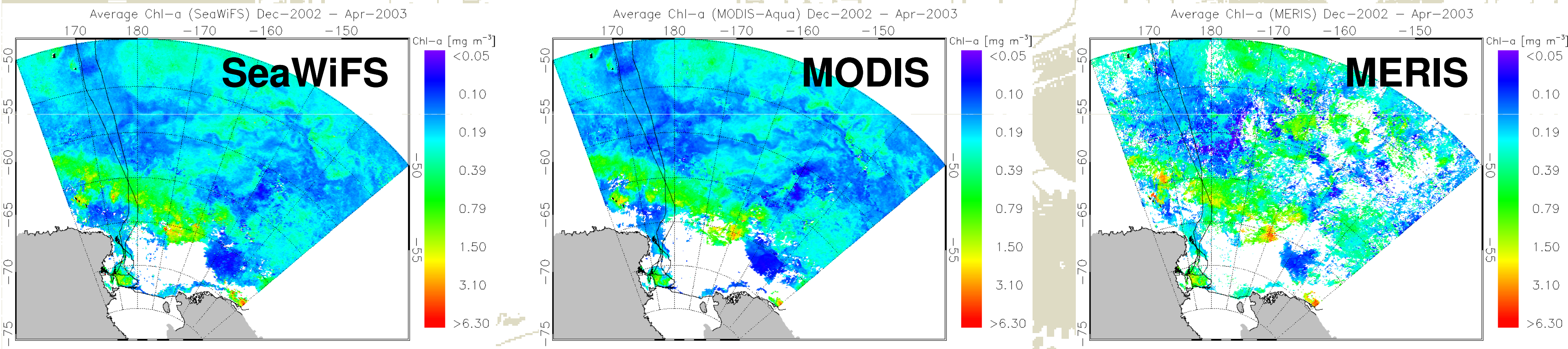
- ELF has been compared with **SeaWiFS**, **MODIS-Aqua** and **MERIS** (satellite radiometers)
- **MERIS needs vicarious calibrations** (ELF can calibrate MERIS)





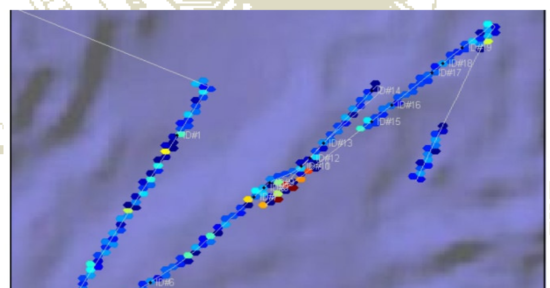
ELF calibration of MERIS

- Let's look at radiometers data **after ELF calibration of MERIS** (December 2002 – February 2003)
- Now all radiometers have **similar values**



POLI

- **POLI (portable lidar) is the evolution of ELF (patented)**
- **All the subsystems, i.e. laser source, collecting telescope, detection optics and acquisition electronics (patented) are miniaturized: the apparatus is contained in a fly case of $0.7 \times 0.7 \times 0.8\ m^3$**



Oil spill-August 2009

Conclusions and acknowledgements

- The atmospheric lidar is a powerful tool for pollution monitoring (power plants) and environmental research (volcanic plumes)
- ENEA Laser Applications Section provided marine scientists with sensors, HW systems and SW applications (pigment measurement, satellite cal/val, oil spill detection)
- The authors are deeply grateful to Roberta Fantoni and the personnel of ENEA Laser Applications Section

Thank you all for your attention!
I'm ready (?) for your questions…