Fluorescence Lidar from satellite: concept and applications

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We present a feasibility study for a satellite borne fluorescence Lidar. The instrument is based on technologies which are either already available, or in an advanced state of development. In particular, the laser transmitter is derived from the experience acquired in the development of the laser transmitter for the ADM-Aeolus ESA mission; the collection optics is based on recent studies on large aperture deployable mirrors (ESA projects ALC, Advanced Lidar Concept, and LATT, Large Aperture Telescope Technology). Several applications for Earth observation are presented and discussed, in particular related to vegetation fluorescence monitoring and oil pollution on the ocean surface, including polar caps.

I. Introduction

THE use of Lidar techniques from satellites is one of the new frontiers in the Earth observation from space. Nonetheless, a Lidar system requires the synergical operation of several technologies, related to the laser source, the signal collecting optics, the detectors, the on board power supply and payload management systems.

So far, technological challenges have limited the number of operative satellite-borne Lidar missions. Among the most recent ones, we can recall the NASA mission ICEsat/GLAS[1], launched in 2003 and operative up to 2009, and CALIPSO/CALIOP, launched in 2007 [2]. The European Space Agency (ESA) is currently engaged in a significant

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effort on this area, in view of the launch of the ADM-AEOLUS mission, which includes the Lidar instrument named ALADIN, and in the planned mission EarthCARE (payload ATLID, scheduled in 2015).

Nowadays, the type of Lidar techniques employed in the current or planned missions is essentially based on the elastic backscattering from the surface (GLAS) for altimetry applications, or on the atmospheric aerosols for applications related to the monitoring and characterization of the aerosol itself (CALIOP, ATLID), or to the measurement of wind speed (ALADIN).

The level of technological development reached by laser devices for space operation (in particular, the device developed by SELEX Galileo for the ALADIN system mentioned above[3]) and by the deployable, wide aperture optics for signal collection[4], makes conceptually possible the use from satellite of other Lidar methodologies for Earth observation.

This paper describes the development possibilities and the expected performances of a fluorescence Lidar (that is a Lidar capable to detect the inelastic scattering coming from the observed target), operating from a satellite orbiting at low altitude. The possible applications range from ecosystems monitoring (in particular, vegetation[5] and water bodies) and pollution monitoring (for instance, detection of oil spills in the marine environment and on the polar caps). These capabilities open new perspectives for the environmental monitoring at global level.

II. Conceptual scheme for a fluorescence Lidar operating from satellite

A fluorescence Lidar system measures the spontaneous fluorescence emission from a target, subsequent to its illumination by a radiation pulse at a wavelength absorbed by the target itself. The fluorescence emission is an inelastic process which provides information about the physical and chemical characteristics of the target under observation.

Differently from the case of an elastic backscattering Lidar, the fluorescence signal must be spectrally analyzed in order to carry out the relevant information. Moreover, the cross-section for inelastic processes is usually several order of magnitude lower than the cross-section for the elastic scattering process. These elements determine a strong reduction of the signal level on each spectral channel used for the detection, and make it difficult its discrimination from the natural radiation background (in particular from the background originated by the solar radiation diffused by the Earth surface). Both the collected signal and the collected solar background linearly scale with the aperture surface of the collecting optics.

The contribution of the radiance background can be acquired immediately after or before the acquisition of the signal containing the fluorescence contribution, and then subtracted. Assuming a shot-noise limited fluorescence signal S_F and background signal S_B, the overall noise on the fluorescence signal N_F is then given by (Equation 1).

$$N_F \approx \sqrt{S_F} + 2\sqrt{S_B} \tag{1}$$

Therefore, the signal to noise ratio of the fluorescence signal scales as the square root of the collecting optic surface.

The improvement of the signal to noise ratio can also be achieved in other three ways:

- the increase in the laser illumination energy (because, at least at low illumination fluence, the fluorescence signal is proportional to the illumination energy, whereas the solar background is obviously constant);
- the use of a gated detector, the gate of which opens in coincidence with the arrival of the fluorescence signal and for a time window close to the duration of the fluorescence signal itself;
- the reduction of the spot size at ground within acceptable limits (under both the technical and scientific points of view), thus reducing the contribution from solar background.

All these elements set the requirements of the energy emitted by the laser system for the target excitation, of the aperture size and efficiency of the optics used for the signal collection, as well as the capability of the detector to reject the

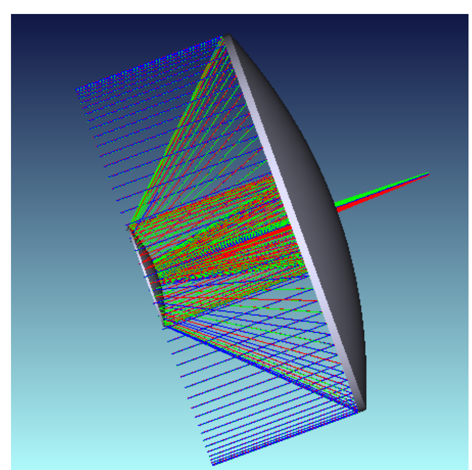

Figure 1. Schematics of the collecting optics, diameter 4 mt, f/# 13

background radiation.

The system that has been devised uses a diode-pumped frequency doubled Nd:YAG laser; Table I reports the emission parameters.

The laser device fulfilling these requirements can be realized by using the subsystems that compose the laser transmitter of the ALADIN instrument. By increasing the number of amplifying units and arranging them into two amplification chains operating alternatively, it should be possible to obtain a pulse energy of 400 mJ at 1064 nm, at

	Elastic channel	Inelastic channel
Wavelength	1064 nm	532 nm
Energy	0.17 Joule	0.23 Joule
Repetition rate	200 Hz	200 Hz
Ground spot diameter	8 m	16 m
Collecting optic surface	9 m^2	9 m^2
Spectral range	-	600-830 nm
Spectral resolution	-	5 nm

Table 1 - Main parameters of the fluorescence Lidar for the satellite platform.

a repetition rate of 200 Hz, still preserving the output beam quality obtained with the original design. This in turn should ensure a conversion efficiency toward the second harmonic in the range of about of 55-57%, sufficient to obtain 230 mJ of output energy at 532 nm.

Both the laser emission wavelengths are simultaneously used by the Lidar device. The emission at 532 nm is used for the excitation of the target fluorescence; the emission at 1064 nm is used for ranging purposes, to predict the target distance and to synchronize the opening of the gate of the spectral detector, as described in details later on.

The fluorescence emitted by the target is collected by a reflecting telescope having a diameter of 4 meters (Figure 1). In order to reduce its weight, and to be compatible with the size allowed by the available launching systems, this optics is realized with an ultrathin deployable mirror. This mirror uses a system for active shape correction based on mechanical actuators [4,6]. This construction technology makes it possible to reduce the specific weight of the mirror around 15 kg/m^2.

The collection optics is then coupled to a spectrometer. An intensified CCD with a gating system based on a microchannel plate image intensifier is placed in the spectrometer focal plane. The detector gate is opened during a short time window (about 100 ns) in coincidence with the estimated time of arrival of the fluorescence signal emitted by the ground target. This feature is critical for reducing the amount of solar radiation collected by the detector and then to improve the signal to noise ratio.

The distance of the sensor from the ground is determined by means of a detection channel that measures the time of flight of the laser pulse from the instrument to the ground and detects the backscattered radiation. This channel uses the laser pulse at 1064 nm, a detector with temporal resolution and it shares the same collecting optics of the

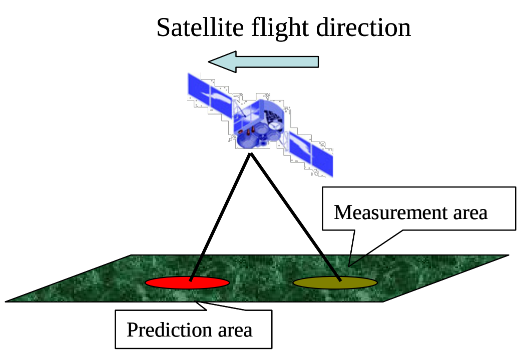

Figure 2. Relationship between the measurement spot for the elastic channel (range prediction) and inelastic channel (fluorescence measurement).

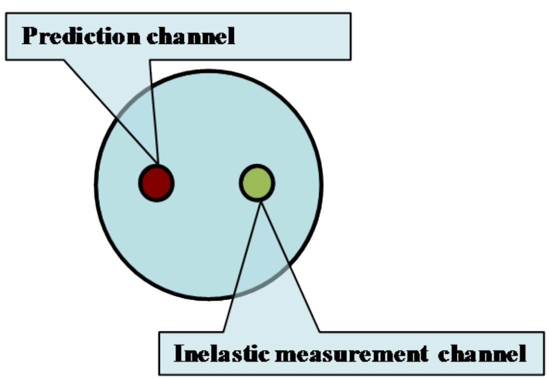

Figure 3. Relationship between the images of the measurement spot for the elastic channel (range prediction) and for the inelastic channel (fluorescence measurement) on the telescope image plane.

fluorescence detection channel. The laser beam and the detector line of sight aim at an advanced position (in terms of orbital trajectory of the satellite) with respect to the measurement point of the fluorescence channel, as depicted in Figures 2 and 3. The measurement of the distance between the satellite and the next measurement spot is then continuously acquired and updated. This information is then exploited to adjust in real time the delay time for the opening of the detector of the inelastic channel.

The spot size at ground of the two beams at 1064 nm and 532 nm is calculated in compliance with the eye safety exposure levels for pulsed lasers.

III. Applications of a satellite-borne fluorescence Lidar

A fluorescence Lidar operating from a satellite will be able to carry out, on a global scale, measurements related to the monitoring of the vegetation and of the marine environment. In particular, the chlorophyll fluorescence and that of plant ancillary pigments provide important information on the photosynthetic activity and on the plant physiology[7]. The study of the vegetation fluorescence at global level by means of hyperspectral passive techniques is considered as a topic of great interest, for instance in the framework of the planned ESA mission named Fluorescence Explorer (FLEX) [8]. These measurements could be efficiently supported by the measurements carried out using an active instrument, as the one described here. Moreover, the presence of an altimetry acquisition channel will allow to provide complementary information on vegetation, such as canopy height, density and foliage vertical distribution.

In the marine environment monitoring, the fluorescence Lidar technique provides information on the characteristics of phytoplankton down to a depth of about ten meters in the water column, complementary to those provided by the traditional passive multispectral imaging techniques. By means of the fluorescence Lidar technique, it is also possible to detect pollutants such as hydrocarbons on the sea surface or immediately beneath it, originated for instance by fuel spills from ships or from offshore oil extraction plants.

IV. Conclusions

The development of a fluorescence Lidar operating from a satellite, for applications to vegetation and marine environment monitoring, is feasible on the basis of the recent advancements in laser technology for space operation and in the development of large aperture, deployable and light weight mirrors. In this paper we proposed a possible instrumental architecture, featuring several *ad-hoc* solutions aimed at optimizing the signal to noise ratio for the detection on the fluorescence channels. We also evaluated the possible applications for operation from a low orbit satellite.

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