S9-5 **Lidar Application to Meteorology and Climate from Ground to Space : Activities in France and in the European Context**

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1. Introduction

Since the early 60's following the discovering of the laser effect in a flash lamp pumped ruby crystal, it has been recognised that LIDAR (or lidar) could play a key role in atmospherics physics in clear air to supplement radar in cloudy atmosphere. Since then meteorological lidars have received strong interest in several fields towards applications in meteorology, climate variability, water cycle (see GEWEX program), atmospherics radiation (see ARM program), pollution, etc. During the first two decades most of the effort have been devoted to develop the relevant lidar techniques. These techniques can be described by the basic light-matter interaction process involved : back scatter lidar, Differential absorption laser (DIAL) lidar, Raman lidar and Doppler lidar.
Along the years the technologies in several key areas has improved and the progresses made in computer, electronics and signal processing have changed radically the perception of the lidar capability in the field of geophysics. At present, the applications are currently conducted from surface and air based platforms, and space applications received a great deal of interest. However, the performance of a lidar instrument in terms of range and sensitivity is still dictated by the "Energy x Area" product i.e. the transmitted laser energy (E) multiplied by the receiver collecting area (A). It is the only flexible parameter with an accumulation of realisations to reach the expected level of performance. The other lidar parameters are pushed to the limit (i.e. optimal) with respect to the detected optical power and signal-to-noise ratio e.g. optical efficiency, photo detector quantum yield, detection bandwidth, etc. The lidar signal as a function of range R can be described by

$$S(R) = K\,R^{-2}\,\beta\,\exp\left[\int_0^R \alpha(y)dy\right] \quad (1)$$

where S is the lidar signal after detection and $K \propto E\,A$ an instrumental constant. Equation (1) applies when the atmospherics parameters vary slowly with respect to the probing pulse duration and photo detector time response. The underlying assumptions break at sharp boundaries between clear air and clouds. In practice, the most limiting quantities to the lidar performance (see (1)) are the atmospherics back scatter (β) and extinction coefficients (α) which may vary by several orders of magnitude depending of weather conditions, location, and lidar probing wavelength. In comparison, the "E A" product may be varied by two or three orders of magnitude at high cost and complexity.

The purpose of the present paper is on the application of meteorological lidars to the retrieval of key parameters in the lower atmosphere : 3D-wind field, number density of trace gases (water vapor, ozone, ...) , optical properties and geometrical characteristics of particles layers i.e. clouds and aerosols. The matter of this paper comes from research activities conducted in France and in the European context (European Space Agency (ESA) and European Community (CE)). Section 2 addresses the present trends in lidar techniques and applications. Section 3 presents ground based applications and lidar networking, sections 4 and 5 address the airborne and space based applications, respectively.

2. Trends

The user needs are high performances (in range, accuracy, reliability, sampling capability, and low cost for operating a lidar instrument. Accordingly, the trends in lidar are directed to the design and operation of compact and automatic instrument with hands-off operation, and continuous operation irrespective of the weather conditions. During the last decade more works have been directed towards new laser technologies and combination of different lidar functions i.e. DIAL and Doppler. An other area of interest is the synergism of active (lidar, radar) and passive remote sensors.

Laser technologies : In the past, most applications call for Q-switched Nd-YAG laser, pulsed CO_2 laser and tuneable Dye laser, and non linear optics techniques i.e. frequency doubling and tripling, Optical Parametric Oscillator (OPO), Raman conversion in high pressure gaze cell. Recently, new laser material (Ti:Sapphire,) and diode pumping have been proposed for "all solid state laser" concept with better reliability and longer lifetime. It is an issue in practice, specially for airborne and space based applications. However, at the present, these new approaches are limited to low and medium energies, while CO_2 laser can provides several Joules per pulse with high spectral characteristics. The Transportable Wind Lidar and airborne WIND lidar presented in sections 3 and 4 are based on single mode 10.6 µm-CO2 lasers.

Micro-lidar : In the recent years the concept of micro lidar becomes a reality for continuous operation (Spinhirne, 1993). The concept of micro-lidar is based on a high repetition rate (1000 Hz or more) and few hundred micro Joule per pulse Nd-YAG laser. The probing pulse is transmitted into the atmosphere through the receiving telescope in order to limit the background noise. The expected performance (see (1)) are restored by an accumulation over a large number of realisations. In a next future, the concept could be applied to DIAL and Doppler applications using diode laser. Such lidar systems are now commercially available in the US, others are being developed in Europe and Japan.

Multifunctions lidar : Most of the time, a lidar instrument is dedicated to a specific application i.e. DIAL or Doppler. So, two lidars (or more) depending on the number of atmospherics parameters to be measured would be necessary to fulfil the measurement objectives (i.e. molecular densities and wind). Then, it is highly desirable to combine the DIAL and Doppler lidar capabilities in a multi functions instrument for the applications. One possibility is to use the Heterodyne Doppler Lidar (HDL) technique for simultaneous range resolved measurements of density and wind velocity in the boundary layer. An accumulation of independent realisations improves the performance with respect to variance reduction of the return signal from distributed aerosol target or hard target. Independent realisations may be obtained in different ways : (i) multi-array receiver (Favreau 1999), or (ii) multi mode transmitter (Drobinski 1999).

Synergism of lidar with microwave and passive remote sensors : A combination of remote sensors bring more information on particles i.e. microphysics and optical properties. It is based on the dependence of scattering properties (scattering efficiency) as a function of a size parameter $x = 2\pi\, r/\lambda$ (r is the radius of spherical particles). The application can combined two lidars transmitting at 0.53 µm and 10.6 µm (Flamant 1996) or one or two lidars and a radar (94 GHz) as it is foreseen in the RALI project (see section 4). Other combination of remote sensors : a back scatter lidar, a POLDER radiometer and a narrow field-of-view IR radiometer are suitable (Sauvage 1999 ; Chepfer 1999).

3. Ground-based application and lidar networking

Monitoring : In 1994-95, two back scatter lidars have been involved in a study dedicated to the Paris heat island effect during the winter season and its connection with pollution episodes. One lidar was located downtown Paris, while the second lidar was located in a pre rural area. The back scatter lidar data provided with information on the time variation of the convective planetary boundary layer at the two locations for comparison (Dupont et al, 1999 ; Menut et al., 1999). On both sites, the lidar data have been completed with sodar information and in situ measurements. This preliminary study has been followed in 1998 and in 1999 by a more complete study at the meso scale involving several aircraft equipped with in situ probes. The objective is to identify polluted air coming out from Paris and to develop a forecast skill. These two studies will be followed in 2001 by a new field campaign in the Marseille area, to study the interaction with dynamical forcing by sea breeze circulation and the flow in the Rhone valley and Durance valley. A transportable Wind Lidar (see below), O3-DIAL lidars, and two airborne lidars a H2O-DIAL lidar and the "WIND" lidar will be involved in this study (see section 4).

Lidar Networking : A global lidar networking activity has been conducted in the frame of the ECLIPS program (Platt et al., 1994). A meso-scale lidar networking has been conducted during a field campaign on cirrus clouds in 1989 (Ansmann 1993). More recently, a proposal has been submitted to the European Commission in the framework of the "5th Research and Development Program" to develop a European aerosol lidar network so-called EARLINET. 20 lidar stations spread over Europe are involved in the project.

Satellite validation : Ground-based and airborne lidars have been used during E-LITE in 1994 to validate the data collected by LITE onboard the Space Shuttle Discovery. In 1996-97, ground based lidars have been used to validate the cirrus product delivered by the POLDER polarisation radiometer on ADEOS platform (Chepfer et al., 1999).

Transportable wind lidar (TWL) : A transportable 10 µm-Heterodyne Doppler lidar has been developed as a follow on a Research and Development program on CO2 laser technologies (Drobinski 1998). The lidar is operational in a 20' container with a 3D scanning capability. This action has been used as corner stone for the WIND program to develop an airborne wind lidar (see section 4).

Instrumented Site : Since early 1999 the Pierre Simon Laplace Institut operates a new instrumented site at École Polytechnique in Palaiseau. At present, three lidars (0.53 µm/1.06 µm, TWL and ALTO, see section 4) and a 5.6 GHz radar, plus visible and infrared radiometers are installed for field experiments. A 30 m-instrumented mast will be available mid-1999. More lidars (like LEANDRE-

2, see section 4) and radars will be installed when they are not involved in airborne campaigns

4. Airborne lidar

In France two Aircraft are devoted to remote sensing activities : a turboprop Fokker 27 and a two engine Mystère 20 (Chalon 1998).
A Back scatter lidar so-called "LEANDRE-1" is operational on board the Fokker 27 since 1990 (Bougeault 1993). The lidar can be installed onboard the Mystère 20 (it aws the case for INDOEX in 1999). LEANDRE-1 has been involved in many field campaigns as presented in Table 1.

Table 1 : Field campaigns involving the airborne back scatter lidar LEANDRE-1.

Year	Field Campaigns	Locations	Objectives
1990	PYREX	Pyrénées	Orographic effects, atmospheric flow disturbance and momentum budget
1992	ASTEX-SOFIA	Azores	Stratocumulus life cycle, air-sea interface, MABL
1993	SEMAPHORE	Azores	MABL, ocean/atmosphere interaction
1994	EUCREX	Brittany, France	Cirrus clouds, atmospheric radiation
1994	E-LITE	Northern Europe	Validation of LITE lidar on shuttle
1996	ECRIN	Brittany, France	Atmospheric radiation
1999	INDOEX	Indian Ocean	Direct/indirect aerosol forcing

A water vapor DIAL lidar so called "LEANDRE-2" is operational since 1997. It is operating in the 0.73 µm absorption band of water vapor for the study of transfer processes at the interface of the boundary layer. It has been involved in field campaigns as presented on Table 2.

Table 2 : Field campaigns involving the airborne water vapor DIAL lidar LEANDRE-2.

Year	Field Campaigns	Locations	Objectives
1997	ACE-2	Atlantic Ocean	Direct/indirect aerosol forcing
1998	FETCH	Mediterranean	Ocean/atmosphere interaction
1999	MAP	Alps	Orographic forcing and heavy precipitation, atmospherics flow disturbance

In addition to the two airborne lidars presented above, an ozone DIAL lidar so called "ALTO" is operational since 1997 (Ancellet 1998). It has been involved in several field campaigns.
A wind Doppler lidar so called "WIND" has been developed in French German cooperation (Flamant 1992). A successful ground validation for WIND has been conducted in April 1999, while the first flights have been successfully conducted in June 1999. WIND will be operated during MAP for two weeks to document the orographic effects on the atmospherics flow (1) 3D gravity wave breaking, (2) gap flow in Brenner pass, and (3) potential vorticity banners on the west side of the Alps.
As discussed above, the combination of a lidar and a cloud radar on the same platform is a power full tool for atmospherics radiation objective. A project so called "RALI" combining the back scatter lidar LEANDRE-1 and a 94 GHz radar provided by University Wisconsin has been flown onboard the Fokker 27 during two field campaigns in France and in England in 1998. The target objectives are the retrieval of microphysics and cloud optical properties.

5. Space based lidar

A great deal of work has been devoted to the preparation of future application of lidar in space (Doutriaux-Boucher 1998) and validation of mission concept in the framework of the European Space Agency Four Earth Explorer Core Missions project : (1) the Atmospherics Dynamics Mission and (2) Earth Radiation Mission.
Late 1998, the so-called PICASSO-CENA project submitted jointly by NASA Langley Research Center and Institut Pierre Simon Laplace has been accepted and funded by NASA Headquarter and Centre National d'Études Spatiales (CNES) in France.

ESA "Atmospheric Dynamics mission" : Today, the ESA Atmospherics Dynamics Mission (ADM) is based on 0.355 µm Nd-YAG transmitter and dual channel receiver for molecular signal, and Fizeau receiver for Mie signal. A study has been devoted to the preparation for concept trade-off of the ADM. It has been divided in two parts, (1) Establishment of a back scatter coefficient and atmospherics data base, and (2) a comparison of fundamental of heterodyne detection and direct detection lidars for wind measurements. The final reports have been issued mid 1999 (Vaughan 1998). At present, a study is conducted to validate a multi

wavelength back scatter database and intercompare wind lidar concepts. The study proceeds in two steps, first a field campaign to validate (at least partially) a scaling law derived for the wavelength dependence of atmospherics back scatter between 0.32 µm and 10.6 µm. Second a field campaign to inter compare velocity measurements undertaken by Heterodyne Doppler Lidars operating at 10.6 µm and 2.1 µm, with measurements by Direct Detection Lidars i.e. two-channel Fabry-Perot, Double edge or fringe imager receivers, respectively. The lidar measurements will be validated by radio soundings and ST radar measurements made on site at the Haute Provence Observatory, in France.
In the framework of this project, several studies have been devoted to signal processing for heterodyne Doppler lidar. In addition studies have been conducted to assess to the impact of aspace based wind lidar data on meteorological analysis and weather forecasting.

NASA/CNES/IPSL "PICASSO-CENA" mission: The mission will accommodate (1) a back scatter lidar operating at 0.53 µm (with depolarisation capability) and 1.06 µm, (2) a two channel Infrared Imager (IIR), (3) a high resolution spectrometer working in the oxygen A band and (4) a Wide Angle Camera. The satellite will be launched in 2003. The PICASSO-CENA mission is a follow on of the NASA LITE mission in 1994, and is aiming at improving our knowledge of the clouds and aerosols radiative forcing using synergetic measurements by active and passive sensors. To this respect the PICASSO CENA mission will fly in formation with the afternoon Earth Observing System (EOS/PM) platform to be launched in 2000 and CLOUDSAT (94 GHz radar) accepted by NASA in spring 1999.

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