Universitat Politècnica de Cataluña (UPC)
Department of Signal Theory and Communications

LIDAR Sensing of the Atmosphere:

RECEIVER DESIGN AND INVERSION ALGORITHMS FOR AN ELASTIC SYSTEM.

Doctor-Engineer Thesis

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November 1996
Barcelona, (SPAIN)

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To my parents,
Encarna
and grandparents
Isidre and María.

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Preface

> *History is not made by kings and presidents but by ordinary people doing extraordinary things.*
>
> *TIMES magazine, Aug.1996*

I am indebted to many people who have contributed material, ideas and offered encouragement during this PhD thesis. I would like to offer special thanks to my thesis director and colleague, professor Adolfo Comerón for his confidence during these three years of work, support and willingness to experiment; to professor Gregori Vázquez for his technical help with the Kalman filter and to professor José María Baldasano, head of the Institut de TEcnologia i Modelització Ambiental (ITEMA). I am also particularly grateful to the Escola Universitaria Politècnica del Baix Llobregat and his director, professor Javier Bará, for the large number of resources and means facilitated, both technical in its well equipped laboratories and administrative; to professor Ferrán Canal, who has been sharing the laboratory of Integrated Optics with the LIDAR activity; to professor Don Fay at Queen's University of Belfast for his generous help in proof-reading the draft-copy of this thesis and patient correction of english mistakes and to professor Ramón Pallás for the selected material made available about CF amplifiers and the instrumentation borrowed from the Electronics Department. I also appreciate the company, friendship and helpful collaboration of Carles Puente and Alejandro Rodríguez, members of the lidar team, with whom I have shared many adventures and who have mainly worked in optical and Doppler lidar activities, respectively, and the kind cooperation of Cecilia Soriano at ITEMA. I also appreciate the help and commitment of all the Department staff, in particular, I do thank Joaquim Giner and Alfredo Cano, for their neat work with the lidar receiver, electrical installation and mechanization of some parts of the lidar system; our computer system manager, Josep Maria Haro, for the installation and preparation of the lidar control computer and Juanjo Tomeo for the promptly and ready work in the activities developed. I wish to acknowledge especially the inputs from the following project students under my direction: Alejandro Lansac Catalán, Matthias Thyroff, Joan Manuel Medina Mesa, Joan Capdevila Vives, Raquel Barrera Moreno, Iván Campos Avilés who worked in the area of system development an integration, Joan Manel March i Gonzàlez and Enric Martín Bayes in the area of atmospheric propagation, Daniel Pineda Masnou, Josep Roca Gabarrón, Alex Sanchez Palaso in the area of inversion and imaging algorithms and also the collaboration of Carles Céspedes and Enric Jornet.

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Abstract

LIDAR is an acronym of **LI**ght **D**etection **A**nd **R**anging. In the present case, the elastic lidar techniques are used to remotely sense the atmosphere and to derive quantitative information about its optical parameters.

This thesis comprises the design and operation of an elastic lidar station based on a pulsed *Nd:YAG* laser operating at the *1064-* and *532-nm* wavelengths, in the parts concerning receiver, control systems and inversion algorithms.

Basically, it can be divided in three different parts. The first one (Chaps.1,2,3) encompass the study of the elastic scattering (Rayleigh and Mie) in the atmosphere for link-budget purposes and gives some insight into the interweaving between physical variables such as temperature, pressure and humidity and the scattering phenomena, letting apart any possible extrapolation to meteorological models. From this basis, extinction and backscatter figures for different atmospheric conditions can readily be assessed and as a result a system linked budget is presented. This includes lidar range study, signal-to-noise ratio assessment and photodiode evaluation from custom-made libraries. At the end of the first part system specification is made.

The second part of this work (Chaps.4,5,6) is concerned with the design and implementation of the receiver, synchronization and control systems. The optoelectronic receiver is based on current-feedback amplifiers and features very large gain-bandwidth product. As for the synchronization subsystem, two different units are presented with a view to a future lidar mobile systems, which make room for interspersed scans. Finally, the control system designed is LabView-based and features a distributed control philosophy. For that purpose, lidar bus protocols and signal are specified and built for the actual lidar station.

Finally, the third part encircles the design of inversion algorithms with and without memory (Chaps.7,8). Nonmemory algorithms for homogeneous atmospheres are based on regression curve fitting procedures, such as slope-method and least squares and in instances of inhomogeneous atmospheres they are based on Klett's method and appropriate calibrations. Memory algorithms are based on different stochastic models for the atmosphere and on nonlinear Kalman filtering. In addition to the inversion procedures, error assessment plots are also derived and discussed. Chap.9 describes the measurements carried out with the system this work has contributed to build and the results of applying to them the inversion algorithms discussed in the preceeding chapters.

The inversion of live-scenes involves pollution structure studies, cloud studies (ceilometry, cloud motion and wave clouds, basically) and hints overlap factor error sources.

Francesc Rocadenbosch-Burillo

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Introduction

Optical probing of the atmosphere through light scattering actually predates the invention of the laser. Nevertheless, the superior qualities in regard to power and collimation of even the early ruby lasers made them obvious replacements for the conventional *searchlights* previously used. It was, however, the development of *Q-switching* by McClung and Hellwarth (1962) that made possible the generation of very short, single pulses of laser energy and thereby range-resolved measurements.

Photons are absorbed and scattered by gas molecules of the atmosphere and also by its particulate or droplet constituents. In the case of energy at the visible or near-infrared wavelengths, such scattering is sufficient to permit application of the radar principle to observations of the atmosphere itself. This principle is referred to as *LIDAR,* an acronym for ***LI**ght **D**etection **A**nd **R**anging*.

Even in the visibly clear atmosphere backscattered signal from gases and suspended particles at ranges of several kilometres may readily be detected with laser radars or lidars. It is accordingly possible to detect the presence and location of particulate clouds or layers and, by tracking inhomogeneities in particle concentration, to determine atmospheric structure and motion. Today the processes amenable to laser remote sensing include elastic scattering (i.e. incident and backscattered wavelength coincide) such as Rayleigh and Mie, and inelastic scattering (i.e. the backscatter-signal is wavelength shifted) such as Raman. Other techniques based on resonance scattering, fluorescence, absorption, and differential absorption (DIAL) are also used. These techniques will be discussed further in Chap. 1.

Remote atmospheric monitoring with lidar provides unique advantages when compared to other methods. Namely, they permit specific applications which would be difficult, if not impossible, using standard instrumentation. Some of these advantages are: non-interference with the source effluent monitoring (no gas sample extraction is required), measurements on a spatial scale comparable with atmospheric model predictions and possibility of measurements at ground level or aloft. Application examples include a lidar system mounted aboard the NASA Shuttle that will make remote measurements of the upper atmosphere, airborne laser fluorosensors that might be used to study the dispersion of water effluents from industrial and municipal treatment plants, or laser bathymetry of coastal regions that could be undertaken from helicopters.

This wide range of applications along with an outgrowing environmental concern grants these systems a relevant role in Europe and particularly in Spain, where they are avant-garde. At the *Signal Theory and Communications Dept.* of the *Polytechnic University of Catalonia (UPC)* at Barcelona, Spain, an elastic-backscatter lidar has been developed under the Interministry Committee for Science and Technology (CICYT) grant TIC431-93. The main objective of the project was to gain expertise with the lidar technique, and to develop prototypes in Spain. It is expected this will consolidate a research line encompassing the development of mobile elastic systems, the design of coherent systems allowing the measurement of Doppler shifts, hence the measurement of the radial component of wind velocity, and, in a longer term of lidar systems able to identify chemical species.

Before proceeding further to describe the structure of the chapters, the contents of some of them warrants some comments: This PhD thesis intends to be a report of the author's work in the design of the lidar system, specially in the parts concerning link-budget, receiver systems and inversion algorithms, during the period 1993-1996. In writing this thesis, the author has intended to make it as comprehensive as possible and plenty of references have been included. Yet, since research is an endless activity, some of the circuits presented are being continuously upgraded. In particular, in what regards the inner core of the lidar system electronics, that is, the optoelectronic receiver and the synchronization unit (chapters 4 and 6, repectively), two and sometimes up to three different units of some subsystems have been developed since the beginning of the lidar activities until mid 1996. In the case of the lidar receiver, three different units have been designed and built: two analog and another one digital. Yet, only the latest analog version is reported here because the digital conception is being patented and consequently, it is protected by confidentiality rights.

Next, this is how the different chapters are organized:

The basis of *Chapter 1,* is formed by broad reviews of atmospheric laser remote-sensing techniques and applications as well as an introduction to the lidar system developed in the Department. The first part of this chapter has been written with an eye to providing the reader with some insight into the enormous breadth of measurements that can be undertaken remotely with lasers sensors and into the state-of-the-art. The second part is aimed at giving an overview of the goals and architecture of the elastic-backscatter lidar system currently developed.

Remote sensing of the atmosphere from optical parameters (i.e. extinction- and backscatter-coefficient) is deeply linked with meteorological variables (e.g. temperature, pressure, humidity, etc.) and atmospheric ones (e.g. type of aerosols, clouds, rain, etc.). For this reason, the aim of *Chapter 2* is two-fold: First, especial effort has been made to gather as much information as possible about Rayleigh and Mie scattering, and to relate them, in a semi-quantitative manner and under the simplificated conditions of a standard atmosphere, to the physical parameters of temperature, pressure and relative humidity. Nevertheless, it has been possible to pinpoint the interplay between optical and physical parameters. Furthermore, this study has laid the basis of a computation software, which fulfils a double purpose: first, the easy estimation of the optical parameters under different atmospheric conditions such as rain, fog, hazes, clouds, etc. and second, the possibility of making custom-made synthesis of atmospheric profiles that helps error assessment in the lidar inversion algorithms. The second part of this chapter concentrates on the study of the background solar radiation, (that is, scattered solar radiation from either the sky or the ground), that under daytime operation can often dominate all other forms of noise.

Link-budget and system specifications are dealt with in *Chapter 3.* The basic laser remote-sensing equation is considered with particular care about the impact of system optical trade-offs, photodetector selection, receiver parameters and system noise. The problem of signal-to-noise ratio in the system and its optimization is also considered. This has a direct implication for the lidar range assessment. The great quantity of system parameters that have had to be considered have led the development of a second software package, whose applications encompass optical communications links.

In a lidar system, the backscattering radiation gathered by the receiver is transformed into an electrical signal which can be digitally processed to retrieve information about the concentration of aerosols in the air at different distances and heights.

Chapter 4 concentrates on the electrical and mechanical design of the receiver, under the considerations discussed. Beginning with a comprehensive collection of sensing circuits for the lidar front-end, the chapter progresses to the transimpedance configuration in use. Next, the layout and components of the receiver, which basically comprises transimpedance, conditioning and offset correction stages, are discussed step by step. Finally, bandwidth and noise measurements corroborate the design specifications.

Chapter 5 concentrates on the test and measurement of the key device of the receiver system, the photodetector. The measurement span includes not only characteristic parameters such as quantum efficiency, responsivity, gain, dark current and noise, but also local variations of the responsivity and gain over the active area of the device. In addition, test set-ups and error analysis are presented.

Integration of the lidar system into a test set-up architecture is treated in *Chap. 6*. It comprises the following subsystems: laser emitter, receiver unit, synchronization unit and control unit. The purpose of the test set-up is to provide effective range-resolved calibrations and adjust the synchronization among the different units when they are immersed in the lidar system as a whole. Since the mainstay of test procedures involves the synchronization unit and its protocol signals, it has been considered more convenient and adapted to begin with the design of this unit and to continue with the tests conducted. As an adjunct, the control system is also discussed in a top level fashion.

The retrieval of quantitative information of the atmosphere from lidar-return signals is know as lidar inversion and it requires solving the lidar equation for the constitutive optical parameters, namely, the attenuation (or extinction-coefficient) and the backscatter-coefficient. This is tackled in Chaps.7 and 8. The inversion algorithms presented are aimed only at the assessment of the primary optical parameters. Transmittivity (extinction) and backscatter measurements are meaningful in instances of visibility assessment in fog or hazes, ceilometry studies (cloud height extent) and qualitative mapping of particulate motion in the atmosphere, which is useful to derive tangential wind-speed. The more general problem of relating them to the physical factors of appropriate concern (for example: mass-concentration or particle size distribution of a pollutant source; temperature, pressure and humidity within an observation cell; etc.) constitutes a very breadth problem that would justify a stand-alone research work by itself.

In my opinion, the lidar inversion is in fact a two-fold problem and hence, I have preferred to classify the inversion algorithms into non-memory and memory ones. This depends on whether the algorithm performs pulse-to-pulse inversions with complete independence from past-retrieved information or not. The former kind of algorithms is studied in *Chapter 7.* On this subject there are very few available references, basically, the slope method of Kunz and Leeuw [187] and Klett's algorithm [186]. This chapter addresses the development of efficient non-memory algorithms as well as error assessment methods that enable to work out error inversion plots for each of the algorithms considered. Since no references exist on this subject, assessment of the sensitivity of each algorithm to the different input parameters, correlation hypotheses and system calibration, which very often involve large uncertainties, is also of prime concern.

Memory algorithms are studied in *Chapter 8* and they constitute a major research pole of this thesis since no references are known. As a brief outline, the atmosphere is modelled in a vector form so that for each cell in the lidar beam-path, attenuation and backscatter parameters are sought. The problem is formulated from the point of view of modern control theory and parameter estimation, which leads to the application on nonlinear Kalman filtering and stochastic modelling of the atmosphere. Using these powerful tools, the algorithms presented will do their best to make the most from present and past information deduced from the return signal. Regarding the complexity of these algorithms and in order to somehow grade the filter, the inversions performed in this chapter have worked with synthesized raw-data, leaving for the next chapter their application to real data.

To sum up, the aftermath of the lidar system developed is treated in *Chapter 9*. Analysis and interpretation of the signals obtained through the lidar system are discussed. In addition, this chapter gives a deep insight into the kind of measurements carried out with our lidar and discusses as well the system performance in a real situation, comprising both day- and night-time operation. The demonstrated capabilities of the lidar, the problems limiting full realization of lidar's potential in atmospheric probing and beyond that, the future prospects of the lidar activity in the Department are presented in *Chapter 10,* where concluding remarks are exposed.

Although I have endeavored to be as comprehensive as possible, the possibilities of the designed lidar including the newest digital units designed with a view to a mobile motorized system are already so large that there are bound to be unexploited. For these I apologize.