Concluding remarks and future work guidelines

The design of the UPC lidar station, as far as the receiver systems and inversion algorithms are concerned, represents an innovative contribution to the development of the lidar technique in Spain. The expanding scope of measurements that are possible by this means represents and effective tool to progress in the knowledge of the nature and behaviour of the atmosphere. Along this work, the contributions to the lidar research line have been the following:

In Chap.2, a first software package, *link-atmos,* has been developed in order to ease the study and simulation of the elastic scattering phenomena in the atmosphere (Rayleigh and Mie scattering), which span both monodispersions and polydispersions. As for the study of the elastic scattering, *link-atmos* has enabled the identification, at least in a semi-quantitative way, of the interplay between physical variables such as temperature, pressure and humidity and the extinction- and backscatter-coefficients. Moreover, in conjunction with extensive bibliography, it has made way for the compilation of a database including the distribution functions of the most important atmospheric scatterers (i.e. clouds, rains, hazes and fogs). As for the simulation role of *link-atmos,* it has been oriented to the assessment of link-budget atmospheric conditions and background radiance levels.

Close to Chap.2, Chap.3 has been devoted to system *link-budget*. The atmospheric studies performed in Chap.2, have been used to get a rough-estimate of the lidar range-return signal strength under different atmospheric conditions. With a view to the design of future elastic lidar configurations, such as the mobile system mentioned in the *Introduction* of this work and in *Sect.1.1, Chap.6,* a second software package, *link-budget,* has been developed. With *link-budged* software it has been possible to analyse lidar system performance sensitivity to virtually any optical or electrical parameter. For instance, this includes, range-studies, signal-to-noise ratio assessment, optical overlap factor trade-offs, atmospheric condition simulation, NEP evaluation from raw-data measurements and photodiode selection. This last point means that parametric studies can readily be made from commercially available photodiode libraries, including both PIN and APDs.

Working on the ground of the link-budget system specification given in Chap.3, Chap.4, 5 and 6, tackle the design, test and measurement of the hardware subsystems of the lidar architecture. Thus, Chap.4 has presented a versatile optoelectronic receiver, featuring wide-band *(10 MHz),* high gain ($\approx 10^5\Omega$) and low-noise ($NEP \approx 70\, fW{\cdot}Hz^{-1/2}$). The design attainments have been twofold: first, wide gain-bandwidth products in excess of *500 MHz* for a single operational-amplifier-based stage have been achieved by making the most of the new technologies available. In the field of operational amplifiers, these are based on current-feedback topologies rather that on conventional voltage-feedback ones. Second, receiver versatility has enabled operation both as a synchronized DC-coupled lidar receiver and as a general-purpose AC-coupled optical communications receiver featuring very low thermal-drift (Sect.5, Chap.4).

APD characterization in Chap.5 has yielded test set-ups and measurement procedures to facilitate reliable evaluation of key photodiode parameters such as quantum efficiency, responsivity and multiplication factor.

For system integration purposes, a new category of control systems based on virtual instruments *(VIs)* rather that on specific purpose-made control units has been implemented in Chap.6. Since VIs combine interface cards and top-level user-made software, the operation of such instruments is easily to redefine. At this stage, the versatility of LabView control software together with an architecture based on efficient communication protocols amongst the lidar subsystems has enabled reliable and easy system integration. Hence, the main contribution of this chapter encircles architectural specification and implementation of top-level lidar bus protocols that embody lidar system integration into a LabView-based distributed control program. By following such bottom-up design approach, all the actual lidar subsystems can easily be integrated in future lidar architectures such as the mobile system in mind or the high-power optical fibre solution discussed in Sect.4.1, Chap.1.

Likewise, the synchronization unit of Sect.2 Chap.6 works on the same basis. In spite of the fact that this unit can ultimately be made redundant in the present application, it is a need in any lidar system having scan possibilities. Being aware that this is the case of the mobile system, two different synchronization units prototypes have paved the way for the short future. A posteriori, the μP-based solution is the most reliable solution, mainly because time delay accuracy *(25 ns)* is crystal-controlled and delay nonlinearities, which are the most concerning factor in the analog prototype, can duly be minimized.

Finally, Chaps.7 and 8 have concentrated on the design of efficient inversion algorithms. From the outset, the available references were very few ([186][187]) and except for Klett's method they reduced to classical regression fitting algorithms. The research results in this area have two branches:

On the one hand, by appropriate synthesis of extinction-backscatter profiles and lidar-signal simulation it has been possible to derive extensive plots where each nonmemory algorithm is parameterized for the correlating hypothesis and system parameters at play. This has yielded *link-detect* software package, which obviously represents a useful tool for future evaluation of new algorithms under development. Since Klett's method is the only nonmemory algorithm that is able to cope with inhomogeneous situations, and hence, a very attractive algorithm, the error assessment studies have concentrated on the identification of the most critic calibration parameters. In this way, it has been possible to develop more complex hybrid solutions which rely on norm-minimization criteria, efficient calibration methods and slice-range processing (see also Sect.2.1 Chap.9). This has yielded the best practical solutions.

On the other hand, a major research pole of this work to solve the inversion problem is the design of memory algorithms based on nonlinear Kalman filtering. Even though the inversion by Kalman filtering is still incipient, and for the time being it reduces to live-scene inversions of cloudy areas, the adaptive behaviour of the filter holds promise of being a preferred algorithm in the medium future together with hybrid Klett's method discussed above. The fact that the actual measurement data received on any particular sample run is weighted with past retrieved information as time goes on along with the fact that stationarity is not a necessary assumption, made of this filter an attractive research line to consider. Furthermore the effort made to develop a first parallel array of filters (in fact, a systolic design) and the know-how acquired encourages this aim.

Yet, even though excellent results have come from *link-detect* simulations that worked with simulated Gauss-Markov dynamic atmospheres (Sect.4, Chap.8) and from its incipient application to cloudy live-scenes, the main drawbacks of the filter are still the start-up problem, the need for atmospheric models that are closer to the underlying physical situation and the parallel implementation of the filter. The latter point has really been achieved in the undersampling filter of Chap.8 and Chap.9 even though, only relative values for the backscatter variable are inverted.

If an attempt were made to grade the inversion algorithms developed this should balance computational efficiency and simplicity with errors due to nonmemory behaviour. Under these assumptions, hybrid Klett's method (Chap.7, Sect.4 and Chap.9, Sect.2.1.2) would outweigh the undersampling Kalman filter.

Finally, the research lines which have been developed during the measurement campaign (Chap.9) present two branches: *transmissometry* in *clear air* conditions (Sect.3, Chap.9) and *cloud observation.* The former comprises detection of the atmospheric stratification and quantitative mapping of the absolute extinction-coefficient for each observation cell *(7.5 m)*. The latter scopes ceilometry studies, i.e. cloud height extent determination and virtually the complete observation of clouds in general. This encompasses the measurement of layer thickness or cloud top height, even in situations where attenuation is as large as $50\ km^{-1}$. Additionally, very tenuous cirrus clouds at approximately 6-km height, invisible to the eye, have readily been detected and their structure and shape mapped. The possibility, for moderate extinctions $(10\ km^{-1})$, of retrieving quantitative height-time absolute extinction profiles, has enabled simultaneous monitorization of layer cloud motion.

Since these figures can be estimated on a very small spatial scale (*15 m* or twice the length of the observation cell), they can easily be compared to atmospheric models to predict their impact on the assessment of the mixing depth, transport and diffusion mechanisms of the natural atmosphere. On this ground, it would be valuable to correlate the extinction profiles with other remote sensing systems such as meteorological radars and balloon-borne instrumentation, even though Chap.9 reported values are in close agreement with referenced sources [9][25].

A prominent point derived from the measurements of Chap.9, Sect.1 is that the interpretation of short-range lidar measurements must take proper account of the *optical overlap factor*. Thus, misalignment of the optical system, which is further complicated by the actual biaxial arrangement, in more than approximately $50\ \mu rad$, can lead to misinterpretation of even long-range measurements. In addition, the radiation from a target plane located at short or intermediate ranges from the telescope is not focused in the focal plane. Since the backscatter-coefficient in not retrieved by differential methods, the overlap factor may severely hamper the system calibration and hence, retrieval of absolute figures for the backscatter-coefficient may be impossible. From the discussion about the overlap factor given in Sect.1.2, Chap.3, Sect.1, Chap.9 and Ap.2, it can be concluded that the angular mechanic resolution is the top factor limiting the accuracy of the system built.

To sum up, the demonstrated capabilities of the elastic lidar technique in atmospheric probing have been indicated in the preceding chapters. The design in this PhD thesis of an elastic lidar station (Chap.1), especially the parts concerning system link-budget (Chap.3), systems in reception (Chaps.4,5) and control (Chap.6) and inversion algorithms (Chaps.7,8) has proved the feasibility of the UPC lidar system as an efficient optical radar (Chap.9).

Regarding future work guidelines, it would be highly valuable the measurement of wind speed vector components and vorticity, smoke plume opacity over industrial areas and gaseous components of the atmosphere.

It is foreseeable that in the nearest future efforts will be devoted to add mobility and angular scanning features to the present elastic system. This will entail redesigning a system around a smaller (and hence less powerful) laser, for which the experience acquired in the work done for this thesis will be most valuable.

Actually, the electronics of the core of scanning system have already been discussed in Sect.1.1, Chap.6, and two synchronization units have been built with a view to the short future. The indetermination and mechanical problems still existing in what respects the overlap factor, will have to be addressed for the mobile system as well as for the fixed one.

In addition to the elastic lidar possibilities, many of which have been treated along this work (Chap.9), the potential benefits from the Doppler effect promise excellent results in the determination of the radial component of the wind speed and the detection of wind shear effects. Work is already under way, in the frame of another thesis, to incorporate the wind speed measurement capability to the present fixed system, before including it into a mobile one.

In a longer term, the determination of presence of chemical species in the atmosphere is also considered. As it has been discussed in Chap.1, this kind of measurements can be made by means of Raman systems, which are used as long range spectroscopic probes. The most noteworthy feature of Raman scattering is that the laser wavelength does not have to be tuned across an absorption line since the spectral information is given by the frequency shift of the emission, which is independent of the laser wavelength. Likewise, these systems can be used to retrieve temperature profiles at ranges over several kilometres. For the time being, the development of such systems, that should provide a scanning facility to map, for example, pollutant gaseous emissions over predefined urban-industrial areas, is high cost and complex.

A further point to bear in mind is the research for eye-safe laser sources, though this is often hampered by the lack of suitable photdetectors at wavelengths longer than $2\ \mu m$.

Work on the inversion algorithms, especially in what concerns the Kalman filter solutions proposed, is to be pursued, as they hold promise of being particularly useful in situations where continuous tracking of the atmosphere is wished.

In brief, lidar has much to offer in a wide range of applications concerned with meteorology, air pollution monitoring and atmospheric research.