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RAMAN LIDAR SIGNAL FILTERING IN WATER VAPOR REMOTE SENSING

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Abstract − A Raman lidar (Light Detection And Ranging) can be implemented in the straightforward fashion illustrated in Fig. 1. The system operates by transmitting a laser pulse of arbitrary wavelength λ_0 and recording radiation backscattered from the atmosphere as function of time to provide range information in a similar manner to a radar system. The return signal contains a strong elastically scattered component (at λ_0) that is useful for profiling clouds and aerosols and also weaker inelastically scattered components that provide chemical-specific information. For profiling water vapor, we use components produced by vibrational Raman effect that produces energy shifts characteristic of the molecules in the atmosphere (3652 cm^{-1} for water vapor, 2331 cm^{-1} for nitrogen). The aim of this paper is to process lidar backscattered signal that contains water vapor and aerosol information in order to improve their recovery. Since they are affected by different kinds of noise, an appropriate filtering, with an improved recovery, represents a way to get good estimates of the above components.

Keywords: Lidar, Remote Sensing, Atmospheric Characterization.

1. BACKGROUND

The water-vapor mixing ratio (grams of water per kilogram of dry air) as a function of range *w(z)* is proportional to the ratio of the number density of water vapor to nitrogen:

$$w(z)\alpha\frac{n_{wv}(z)}{n_{nit}(z)} \quad (1)$$

The nitrogen detection channel is always operated [1] with a filter that transmits the nitrogen Raman signal. The water-vapor channel, normally operated with a filter that transmits the water-vapor Raman signal, is also operated with a filter that transmits the nitrogen Raman signal. Direct ratioing of the water-vapor and nitrogen channels operated with their normal filters and collecting various constants into k_{meas} yields $R_{meas}(z)$:

$$R_{meas}(z)=\frac{S_{wv,\lambda_{wv}}(z)}{S_{nit,\lambda_{nit}}(z)} \quad (2)$$

$$R_{meas}(z)=k_{meas}\frac{T_{wv,\lambda_{wv}}O_{wv,\lambda_{vw}}qn}{T_{nit,\lambda_{nit}}O_{nit,\lambda_{nit}}qn} \quad (2)$$

This ratio, which is close to goal represented in relation (1), is independent of laser power and attenuation of the laser beam propagating to the observation point and has the range-squared signal dependence removed [2]. Three ratio terms remain to be dealt with. The filter transmission functions *T* have little if any range dependence (created only by the change of the angle of the ray bundles passing through the filter with range), and any range dependence becomes negligible by forming the ratio of two channels with similar filters [3]; the term is only present in these equations for completeness. The ratio of the overlap terms *O* for the two channels can lead to a significant correction. At various intervals during data acquisition, a nitrogen interference filter replaces the water-vapor filter in the water-vapor channel, and a measurement is recorded in this configuration. By use of Eq. (2) to calculate the ratio of the water-vapor channel and nitrogen channel signals, almost all the terms drop out because both channels are detecting nitrogen; the remaining terms form a calibration signal $R_{cal}(z)$:

$$R_{cal}(z)=\frac{S_{wv,\lambda_{wv}}(z)}{S_{nit,\lambda_{nit}}(z)} \quad (3)$$

$$R_{cal}(z)=k_{cal}\frac{T_{wv,\lambda_{wv}}(z)O_{wv,\lambda_{vw}}(z)}{T_{nit,\lambda_{nit}}(z)O_{nit,\lambda_{nit}}(z)} \quad (3)$$

Finally, taking the ratio of Eqs (2) and (3), we obtain

$$\frac{R_{meas}(z)}{R_{cal}(z)}=\frac{k_{meas}}{k_{cal}}\frac{T_{wv,\lambda_{wv}}}{T_{wv,\lambda_{nit}}}\frac{O_{wv,\lambda_{wv}}}{O_{wv,\lambda_{nit}}}\frac{q}{q_{nit}}\frac{n}{n_{nit}} \quad (4)$$

This result is similar to Eq. (2), but the ratio of the two overlap terms is now for a single channel (water vapor) although observed at two wavelengths, and would be strictly unity in a perfectly achromatic system. The overall ratio expressed in Eq.(4) should therefore be a better approximation to the goal represented in relation (1). In spite of optical filters included in the experimental apparatus, there is a need of further filtering, by using signal digital filtering. Eq.(2) and Eq.(4) have been semplified in their specifications in order to make them easier in terms of meaning.

2. EXPERIMENTAL APPARATUS

The lidar system (UNI-LE, 40 20'N,18 6E) operates in Physics Department of The University of Lecce (Italy). It uses an XeF excimer laser (lambda Physik LPX 210i) as illustrated in the photograph in Fig.1. An unstable cavity has been applied to the laser source to get a low divergence of laser beam. The laser, equipped with an unstable cavity, sends pulses of 150 mJ, with 30 ns of duration, 30x20 mm^2 and about 0.3 mRad of divergence. The collected backscattered radiation is obtained by a newtonian telescope whose primary mirror has 3 cm of diameter and 120 cm of focal length. The gathered radiation is spatially filtered by a diaphragm and separated in three different spectral channels corresponding to water vapor Raman radiation, to elastically scattered radiation and nitrogen scattered Raman radiation.

Fig. 1. System view

3. WATER VAPOR SIGNAL FILTERING

In the laser detection by means of lidar, there are five types of noise that can be treated with: *backscattering noise, quantum noise, statistical noise, dark current noise and noise due to optical elements.*

To discriminate noises [4] from the main signal that is backscattered from sky, we are investigating on the use of appropriate digital filtering to be utilized in order to retrieve a noiseless signal. This approach is different from the current one that uses a poissonian averaging of collected data. In the first level of our investigation, we prefer to employ filters that preserve either amplitude information and phase one. In this outlook, we have to use various filtering technique to improve data retrieval from backscatterd signal [5]; that is, Finite-Impulse Response (FIR) or nonrecursive filters, least-squares filters, adaptative filters and ARMA (Auto Regressive Moving Average), etc. We have chosen to use normal FIR (Fig.2) and least-squares filters so that phase and amplitude information contained in the lidar signal must be preserved.

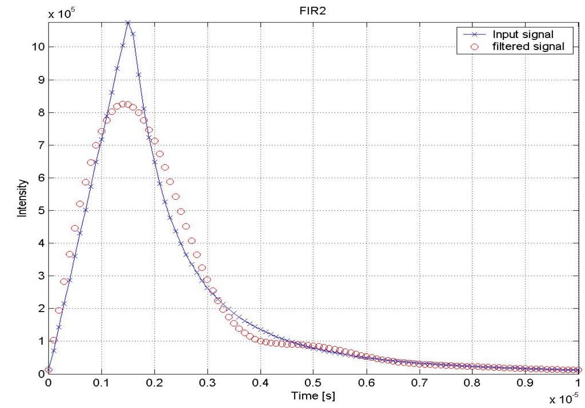

Fig. 2. Water vapor signal filtering

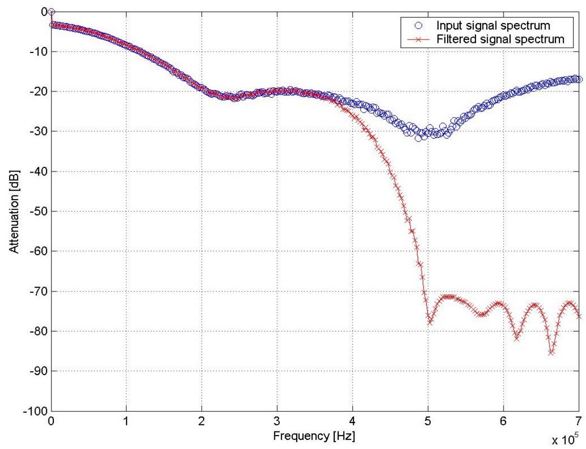

Fig. 3. Normal FIR filter outputs

To design the filter, the following steps have been performed:

-*specifications for digital filter*: low-pass filter with sampling frequency f_s=10GHz, cutoff frequency f_c=400 kHz and passband ripple of 1 dB or less as specified in Fig.3;

-*the approximation problem*: obtain an input-output characterization of the filter (such as transfer function) that satisfies the specifications;

-*the realization problem*: obtain a realization that defines the internal structure of filter that has transfer function *H(z)*. The realization is chosen to optimize criteria associated with the actual computation. The resulting vector of filtering must be put in the following equation in order to obtain aerosol extinction profile that is correlated to water vapor, that is:

$$\alpha^{aer}(z) = \frac{\frac{d}{dz}\ln\left(\frac{z^2 s}{\rho}\right) - \alpha_{\lambda_L}^{ray}(z)\left(1-\left(\frac{\lambda_L}{\lambda_R}\right)^4\right)}{1+\left(\frac{\lambda_L}{\lambda_R}\right)^k} \qquad (5)$$

where α is extinction coefficient (aerosol and rayleigh ones), ρ stands for air density, z^2s is the filtered signal, λ_L and λ_R are respectively lidar wavelength and Raman one.

Quantitative measurements [6] of aerosol optical properties using a lidar system which measures only aerosol backscatter require accurate system calibration and assumptions regarding aerosol optical properties [7]. Lidar systems which scan can alleviate some of these restrictions by using a multiangle integral solution of the lidar equation to solve for both backscatter and extinction. However, this method requires horizontal homogeneity of the aerosol.

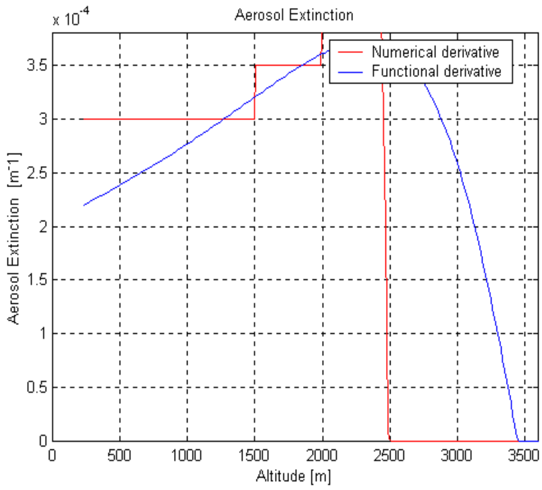

Fig. 4. Aerosol extinction trend

Aerosol extinction is the final coefficient of this work that represents a goodness factor for the method used in this paper. We summarize the path followed to reach aerosol extinction trend shown in Fig.4:

- signal samples are acquired from the experimental apparatus described in section 2;
- a designed filtering system is utilized to discriminate actual and signficant signal from noise, instead of producing signal from average poissonian-calculated sample vector;
- aerosol extinction is computed from Eq.(5) in two version: numerically and functionally. The numerical way has a step trend. Extinction calculated according to numerical way becomes zero when altitude is 2500 meters. That is a good value according to specific and scientific literature.

A no correct accomplishment of data acquisition and data analysis can determine a miscalculation in the estimation of the aerosol coefficient and of the the statistical error. For this reason, huge care is necessary in handling data in order to retrieve the extinction coefficient profile starting from Raman signals. [8].

The results reported in Fig. 4 reflect the noctitime operations using the above XeF excimer laser; the outgoing wavelength is at 351 nm. In general, for 351nm XeF excimer, the return Raman N_2 wavelength is at 383 nm and the return Raman O_2 at 372 nm. Thus the total aerosol extinction measured by lidar is actually the sum of the aerosol extinction coefficients at 351 nm and at 383 nm if the Raman nitrogen signal is used or the sum of the aerosol extinction coefficients at 351 nm and 372 nm if the Raman oxygen signal is used.

4. SUMMARY AND CONCLUSIONS

In this paper we have presented an opportunity of using digital filtering in order to retrieve lidar signal data that contain water vapor.

Water vapor and aerosols are two significant atmospheric components that are generally detected for a better knowledge of weather and climate. Aerosols play a key role in Earth's radiative balance and in the global climate, since they influence the radiation balance through two crucial processes: directly, by scattering and absorbing solar radiation, and indirectly, by acting as cloud condensation nuclei, and thus dramatically affecting the optical properties of clouds. The water vapor mixing ratio, on the other hand, is useful as a tracer of air parcel and in understanding energy transport mechanisms within the atmosphere.

The technical items faced in this paper are part of lidar network that allows to establish a climatological data set of aerosol and water vapour vertical distributions in a quantitative and co-ordinated approach. The main objectives of the lidar network are to:

- perform lidar measurements of water vapor and aerosols on a fixed schedule to provide an unbiased statistically significant data set that allows to investigate the correlation between these two interesting atmospheric parameters besides providing quantification of their distribution and variability in space and time. Combined Rayleigh-Raman lidars based on a XeF excimer laser (351 nm) will be used in the network;
- perform additional measurements to specify address important processes that are localized either in space or time such as those due to saharian dust outbreak, large forest fires and photochemical smog episodes. Continuous lidar measurements during the whole duration of the investigated event will be carried out;
- provide ground truth for present and future satellite missions dedicated to the retrieval of the global water vapor and aerosols distribution. To this end the water vapor columnar content and the aerosol optical depth will be compared with satellite data.

It is believed that the data set provided as a result of the research activity performed within this network will be surely helpful for the scientific community, allowing a better modeling and a deeper understanding of the atmospherical Physics.

Despite the presence of interference filters inside the lidar instrumentation described in this paper, lidar signal output is affected by more noise. So far, in scientific literature, we encountered the use of poissonian average, for each lidar acquisition, in order to retrieve water vapor; nevertheless, the approach provided by the present paper overcomes the above procedure and by using filtering [9], it is possibile to remove noise, to get accurate acquisition and to have “one shot” (for further development) acquisition.

REFERENCES

[1] M.S. Unlu, and S. Strite, "Resonant cavity enhanced photonic devices" *J.Appl. Phys*., vol.78, no.2, pp. 607-639, July 1995;

[2] J.E.M. Goldsmith, F.H. Blair, S.E. Bisson, D.D. Turner, Turn-key Raman lidar for profiling atmospheric water vapor, clouds, and aerosols, *Applied Optics*, Vol.37, No.21, July, 1998;

[3] A. Ansmann, M. Riebesell, U. Wandinger, C. Weitkamp, E. Voss, W. Lahmann, W. Michaelis, *Applied Physics*, B55, 18, 1992;

[4] P.A. Lynn, W. Fuerst, *Digital signal processing with computer applications*, John Wiley & Sons, New York, 1993;

[5] M. Belanger, Digital processing of signals, 2nd edition, *Wiley*, Chichester, 1989;

[6] J.D. Klett, Stable analytical inversion solution for processing lidar returns, *Appl. Opt*.,20, 211-220, 1981.

[7] F.G. Fernald, Analysis of atmospheric lidar observations: Some components, *Appl. Opt*., 23, 625-653, 1984.

[8] D. Whiteman, Application of statistical methods to the determination of slope in lidar data, *Appl. Opt.* Vol. 38 No.15, 3360-3369, 1999.

[9] R.W. Hamming, Digital filters, 2nd edition, *Prentice-Hall*, Englewood Cliffs, 1983.