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THE NOTION OF VARIANCE IN THE DATA ANALYSIS OF RAYLEIGH-MIE LIDAR SIGNAL

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INTRODUCTION

The usual way to analyse the signal of a Rayleigh-Mie lidar, and in general any incoherent lidar, is to sum the raw signal for each altitude channel and for a given number of laser shots, corresponding in general to an integration time of a few minutes. It is then possible to determine the mean vertical profile of the measured parameter (molecular density and temperature, Mie scattering ratio, ...) and the fluctuations around the mean profile due to atmospheric phenomena (gravity waves, thin aerosol layers). Due to the signal to noise ratio of the measurements which increases with integration time and vertical smoothing, it is only possible to detect perturbations with periods and vertical wavelengths long enough to be above the noise. In order to have access to perturbations with shorter time and vertical scales, at least on a statistical sense, we propose a new method to analyse lidar signals. This method is based on the computation of the variance of the signal for short time and vertical intervals and of the summation of this variance over a large number of elementary intervals. The results are then compared to the theoretical variance in absence of atmospheric perturbations due to the shot noise. We shall present the theoretical basis of the variance analysis and two geophysical applications of this technique that have been made using the two French Rayleigh lidars in the South of France. The first application is the estimation of the gravity wave energy in the upper stratosphere and in the mesosphere and the second one is the precise determination of the top of the stratospheric aerosol layer. Finally we shall present other potential applications of this method, the detection of mesospheric particles and the estimation of stratospheric vertical winds.

VARIANCE ANALYSYS

We consider the signal of a Rayleigh-Mie lidar in the middle atmosphere operated in photon-counting mode. The variance of the signal due to atmospheric fluctuations is computed in small elementary intervals (Δt, Δz) using the formula:

$$V(z_i,t_j) = [S(z_i,t_j) - {}^1/_2\,(S(z_{i+1},t_j) + S(z_{i-1},t_j))]^2 - {}^3/_2\,S(z_i,t_j)$$

where $S(z_i,t_j)$ is the signal at altitude z_i and time t_j in raw counts,

${}^3/_2\,S(z_i,t_j)$ represent the expected value of the instrumental variance, that is to say the variance of the signal in absence of atmospheric fluctuations assuming a Poisson statistics of the counts.

This variance is averaged over N_t time intervals and N_z altitude intervals in order to increase the signal to noise ratio.

We are able to detect atmospheric perturbations with a 95% confidence interval if the measured atmospheric variance is above 2 standard deviation of the instrumental variance. With these hypotheses, atmospheric perturbations of a relative r.m.s. amplitude δ can be detected if the averaging of the variance is made over N elementary intervals with:

$$N = N_t\,N_z > 8 / (\delta^4 S_o(z_i)^2)$$

where $S_o(z_i)$ is the mean signal at altitude z_i.

It is therefore possible to decrease the detectivity threshold of the perturbations by increasing the number of elementary intervals N over which the average is made.

ENERGY OF GRAVITY WAVES

The Rayleigh lidar provides vertical profiles of the total density of the atmosphere above the top of stratospheric aerosol layer (about 30 km) and to about 90 km depending on the signal to noise ratio (Hauchecorne and Chanin, 1980; Chanin and Hauchecorne, 1984; Keckhut et al., 1993). The density obtained is a relative value and has to be normalised at a given altitude with an independent observation if an absolute value is needed. The temperature profile is obtained by integration of the hydrostatic equation. The deviations of the observed density profile from a smooth one is attributed to the presence of gravity waves (GW). It is therefore possible to evaluate the potential energy of the GW directly from the fluctuations of the relative density profiles. The variance of the fluctuations computed as described previously is an estimation of the GW energy in a spectral band-pass defined by a 3 points vertical filter of length 3 Δz with coefficients (-1/2, 1, -1/2) (Hauchecorne et al., 1994). This filter is centred at a wavelength $\lambda \approx 2.4\ \Delta z$ and has a full width at half amplitude equal approximately to $\Delta\lambda \approx \lambda$.

This method has been tested during the DYANA (Dynamic Adapted Network for the Atmosphere) in January-March 1990 using the data of the Biscarrosse Rayleigh lidar (44°N, 1°W) which provided a continuous survey of the density profiles every night of clear sky with temporal and vertical resolutions respectively of 3 min and 0.3 km (Hauchecorne et al., 1994). In order to increase the signal to noise ratio it is possible to degrade these values. In the present study we used 0.3, 0.6, 1.2 and 2.4 km for Δz and 3, 6 and 12 minutes for Δt and the GW energy was computed in 5 layers from 30-45 km to 70-85 km. This method is relatively simple but has the advantage to be fast and to use the raw data. It is therefore not dependent upon data processing errors. In order to verify that it gives a good estimation of GW activity, the results obtained with (Δz=1.2km ,Δt=12 minutes) have been compared with those obtained with a more sophisticated spectral method where the GW energy is integrated in the vertical wavelength range from 1 to 10 km and the measurement noise is assumed to be white and estimated by a statistical method described by Wilson et al. (1991). The correlation of the GW energies obtained during DYANA by the two methods is very satisfactory (correlation coefficient 0.62 in the 30-45 km layer and 0.79 in the 40-55 km layer). The method of the variance has also proved its ability to estimate the energy at shorter scales ($\lambda \approx 0.7$ km) than the standard spectral method.

DETECTION OF THE TOP OF THE STRATOSPHERIC AEROSOL LAYER

Density and temperature profiles obtained by Rayleigh lidars are limited downward to the altitude of the top of the stratospheric aerosol layer (Hauchecorne and Chanin, 1980; Chanin et Hauchecorne, 1984; Keckhut et al., 1993)). This altitude is at about 30 km but varies considerably from night to night and can be as high as 38 km above South of France after strong volcanic eruptions (El Chichon, Pinatubo). It is therefore very important to be able to determine it. This can be done using a 2λ lidar, due to the dependence of the scattering ratio upon the wavelength or a Rayleigh-Raman lidar (Keckhut et al., 1993), but it requires more complex equipment and operation modes than a simple 1λ Rayleigh lidar. We propose to use the method of the variance to estimate this altitude using the signal of a 1λ Rayleigh lidar.

As a matter of fact, the amplitude of short vertical scale fluctuations is limited by the stability of the atmosphere. If the amplitude of a given perturbation is larger than the level of convective instability corresponding to its wavelength, a superadiabatic temperature gradient is created and a turbulent mixing occurs which prevents a further growing of the perturbation. On the contrary, the amplitude of perturbations in aerosol profiles is not limited by a similar mechanism and very strong vertical gradients can occur. As a consequence, the vertical profile of the variance, computed with small Δz values, is at least one order of magnitude higher in the stratospheric aerosol layer than above its top. The altitude obtained by this method as been compared at Haute-Provence Observatory (OHP, 44°N, 6°E) with the results obtained using the 2λ and the Rayleigh Raman methods The agreement obtained for the top of the layer is better than 1 km.

PERSPECTIVES

The method of the variance can be used to detect the presence of Mie scattering at higher altitude and in particular in the summer high and middle latitudes mesosphere where Polar Mesospheric Clouds (PMCs) are formed. PMCs have already been detected directly using scattering ratio profiles (Hansen et al., 1989; Thomas et al., 1994) but the method of the variance will allow a much higher detectivity. A tentative of detection of mesospheric particles during meteor showers has also been made at OHP.

Another application could be the detection of vertical winds induced by gravity waves and turbulence in the stratosphere. The newly developed Doppler Rayleigh lidar in operation at OHP (Chanin et al., 1989; Garnier and Chanin, 1992) gives the components of the horizontal wind from 10 to 60 km, assuming that the vertical wind is negligible compared to the 1 ms^{-1} detectivity of the lidar (the profile obtained in the vertical direction is used as a zero reference). This condition is verified in the stratosphere where the vertical wind is estimated to be a few tenths of ms^{-1}. Using the method of the variance, it would be possible to decrease the threshold of detectivity of vertical wind fluctuations to less than 0.1 ms^{-1} in the lower stratosphere by averaging a large number of elementary intervals. This will be tested in the near future using the OHP Doppler lidar .

In conclusion, the method of the variance has a great potentiality in the analysis of middle atmosphere lidar results, including the study of dynamical parameters as gravity waves and turbulence and the detection of particle layers both in the stratosphere and in the mesosphere.

REFERENCES

CHANIN M.L., A. GARNIER, A. HAUCHECORNE, J. PORTENEUVE, A Doppler Lidar for measuring winds in the middle atmosphere, **Geophys. Res. Let.** , 16, 1273-1276, 1989.

CHANIN M.L., A. HAUCHECORNE, Lidar studies of temperature and density using Rayleigh scattering, **MAP Handbook,** 13, 87-99, 1984.

GARNIER A., M.L. CHANIN, Description of a Doppler Rayleigh lidar for measuring winds in the middle atmosphere, **Applied Physics B**, 55, 35-40, 1992.

HANSEN G., M. SERWAZI, U. VON ZAHN, First detection of a noctilucent cloud by lidar, **Geophys. Res. Lett.,** 16, 1445-1448, 1989.

HAUCHECORNE A., M.L. CHANIN, Density and temperature profiles obtained by lidar between 35 and 70 km, **Geophys. Res. Lett.**, 7, 565-568, 1980.

HAUCHECORNE A., N. GONZALEZ, C. SOUPRAYEN, MANSON A.H., C.E. MEEK, W. SINGER, A.N. FAHRUTDINOVA, U.P. HOPPE, J. BOSKA, J. LASTVICKA, J. SCHEER, E.R. REISIN, H. GRAEF, Gravity wave activity and its relation with prevailing winds during DYANA, **J. Atmos. Terr. Phys.,** 1994, in press.

HAUCHECORNE A., M.L. CHANIN, P. KECKHUT, D. NEDELJKLOVIC, Lidar monitoring of the middle atmosphere and lower atmosphere, **Applied Physics B,** 55, 29, 1992.

KECKHUT P., A. HAUCHECORNE, M.L. CHANIN, A critical review of the data base acquired for the long term surveillance of the middle atmosphere by Rayleigh lidar, **J. Atm. Ocean. Tech.,** 10, 850-867, 1993.

THOMAS L., K.P. MARSH, D.P.? WAREING, M.A. HASSAN, Lidar observations of ice crystals associated with noctilucent clouds at middle latitudes, **Geophys. Res. Lett.,** 21, 385-388, 1994.

WILSON R., M.L. CHANIN, A. HAUCHECORNE, Gravity waves in the middle atmosphere by Rayleigh Lidar, Part. 1 : Case studies, **J. Geophys. Res.,** 96, 5153-5167, 1991.