Observation with a Lidar of the Water Content in Fogs.

A. Dabas, C. Klein
Météo-France, Centre National de Recherches Météorologiques
42 avenue Coriolis, 31100 Toulouse
France
alain.dabas@meteo.fr; celine.klein@meteo.fr

P. Flamant
Centre National de la Recherche Scientifique, Laboratoire de Météorologie Dynamique
Ecole Polytechnique, 91128 Palaiseau cedex
France
pierre.flamant@polytechnique.fr

1. Introduction

When visibility is low on an airport (visibility less than 2000ft and/or cloud ceiling below 200ft), its capacity (number of flights landing or taking off per hour) is significantly reduced (up to ½), causing delays, cancellations, missed connections… The cost for the airport and the companies is high, in particular when the perturbed airport is a hub. The formation of fog cannot be prevented, but a good forecast of the time of its formation or dissipation provided a few hours in advance is of great help. Dedicated forecast systems have thus been developed. At Paris Roissy Charles-de-Gaulle airport (2nd airport in Europe in 2009), a dedicated forecast model called COBEL-ISBA[1,2] is run operationally every hour and provides probabilities of fog presence each ½ hour for the next 12 hours. The current skill of the system is limited. One reason is the complexity of the phenomenon that involves non-linear processes. But another difficulty resides in the lack of observations for characterizing the low-level, meteorological state of the atmosphere at the initial time of the forecast. Presently, there is for instance no observation of the liquid water content inside a fog already formed on the platform. This content is prescribed at a fixed value that may deviate significantly from the real content. Yet, studies[3] have shown that the forecast of fog dissipation time is sensitive to this parameter. The present paper summarizes the result of a preliminary work aimed at assessing the feasibility of a backscatter lidar for measuring vertical profiles of the liquid water content (LWC) inside, and through the whole depth of fog. The measurement principle is based on the existence of a simple relationship between the lidar extinction coefficient and the LWC. The existence of this kind of relationship is suggested by pioneering works carried out in the 70s.

2. Fog.

Different types of fogs exist. It is common to distinguish fogs that are formed locally by a cooling, low level process – generally cooling by infrared emission of the surface uncompensated by down-welling solar light – and fogs formed elsewhere and brought by the prevailing wind. These latter ones are called advective fog, the former, radiation fog. At Roissy Charles de Gaulle, radiation fogs are prevailing. A typical radiation fog has a thickness of a few tens to a few hundreds of meters (see Figure 1).

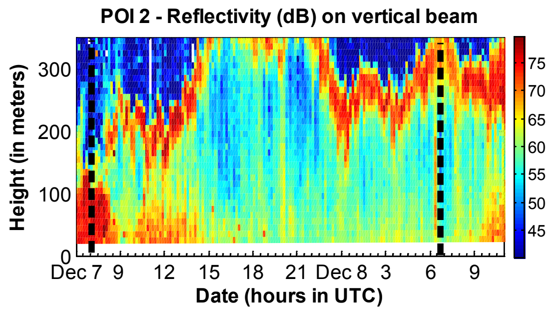

Figure 1: Reflectivity of a sodar echo recorded as a function of height (above the ground – y axis) and time (UTC time – x axis) at Roissy CDG airport on the 7th and 8th of December, 2008. The fog formed on the 7th of December at ~7UTC and dissipated the next day at ~7UTC. The top of the fog layer is marked by the line of reflectivity peak at an altitude varying between 200m and 300m.

It usually forms in the evening when the sun disappears below the horizon and dissipates the next morning when the sun rises and warms again the atmosphere. At Roissy CDG airport, the statistics show that fogs are occurring mostly in the winter, from October to end of March.

Fog is formed by liquid water droplets. A typical size distribution of the droplets is shown in Figure 2. Most of them have a radius of a few hundreds of nanometres. Bigger droplets (radius ~10µm) do also exist, but in a small fraction. Their contribution to the overall LWC is not known precisely because big droplets are very difficult to measure. A typical LWC in a fog is $0.2\ g/m^3$.

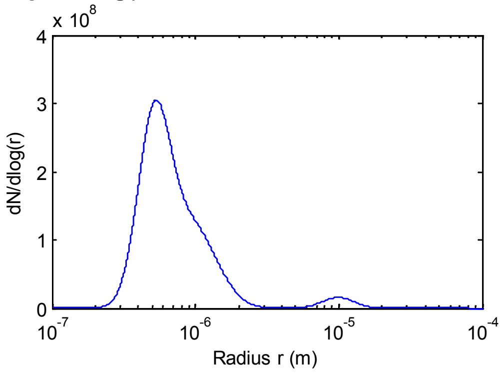

Figure 2: Size distribution of water droplets in a fog (measured experimentally)

3. Measurement specifications.

Fog forecast models need real observations of the vertical profile of the LWC throughout the whole depth of the fog with the following specifications:

- The vertical resolution must be of the order of $\sim 10m$.
- The time resolution must be of the order of $\sim 10\ min$.
- The information must be renewed at least once every hour.
- The relative precision of the LWC information must be 10% or better.

3. Extinction coefficient versus LWC.

The LWC and the extinction coefficient of fog are both related to the size distribution $N(r)$ of water droplets ($N(r)dr$ is the number of droplets with a radius between r and $r + dr$):

$$LWC = \frac{4\pi\rho}{3}\int_0^{+\infty} r^3 N(r)dr$$

where ρ is the water density (in $kg\ m^{-3}$) and

$$\sigma_{ext} = \pi\int_0^{+\infty} r^2 Q_e\left(\frac{2\pi r}{\lambda}\right) N(r)dr$$

Here, $Q_{ext}\,(2\pi r/\lambda)$ is the extinction efficiency defined as the ratio of the extinction cross-section of a droplet by its physical section πr^2. It is a function of the non-dimensional size parameter $x = 2\pi r/\lambda$ and can be computed by the Mie theory. Figure 3 shows the typical shape of Q_{ext} as a function of x. It can be seen that the extinction efficiency can be roughly approximated by a line $Q_{ext}(x) \approx cx$ as long as $x \leq 1$ (or $r \leq \lambda$). If in a fog, $N(r) \approx 0$ for $r \geq \lambda$, than we have

$$LWC \approx \frac{2\lambda\rho}{3\pi c}\,\sigma_{ext}$$

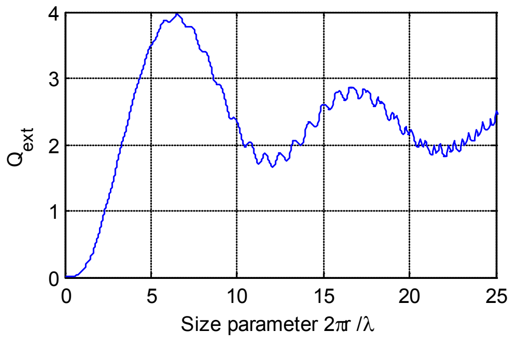

Figure 3: Extinction efficiency as a function of the size parameter (computed for $\boldsymbol{\lambda = 10\mu m}$ and water droplets of radius r and refractive index $\boldsymbol{m = 1.218 + i0.0508}$ in vacuum).

The existence of a possible, linear relationship between the LWC and the extinction coefficient was suggested by Pinnick *et al.* in the late 70s[4]. Pinnick *et al.* gathered and compared experimental measurements of both the LWC and σ_{ext} for a number of fog events and various wavelengths (see Figure 4). They found the linear relationship is a good approximation as long as the wavelength is long. The best results were achieved in the thermal IR. Note that a typical value for the extinction coefficient within fog is $0.001m^{-1}$, but can reach values as high as $0.1m^{-1}$.

4. Direct versus heterodyne detection

Direct and heterodyne detections are both able to provide measurements of extinction coefficients. Figure 5 below shows the CNR and SNR for a heterodyne and a direct detection lidar emitting the same energy ($80mJ$) per pulse at the wavelength of $10.6\mu m$, a repetition rate of $10s^{-1}$, receiving with the same telescope of diameter $10cm$ and accumulating 6000 shots (10 minutes of integration time). A "medium" fog was considered with $\beta = 9.7\ 10^{-6}m^{-1}sr^{-1}$ and $\sigma_{ext} = 1.2\ 10^{-2}m^{-1}$. Note that the SNR is always defined as $SNR =< P >^2/\sigma_P^2$ where P is the lidar signal in direct detection and the square of the heterodyne current in heterodyne detection. The figure shows the heterodyne detection should allow measurements longer ranges.

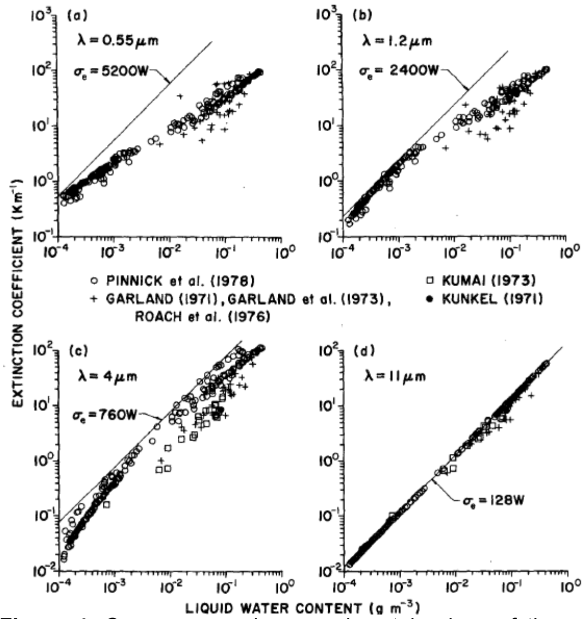

Figure 4: Curves comparing experimental values of the extinction coefficients measured within fog at different wavelengths and the liquid water content. From Pinnick *et al. 1979*.

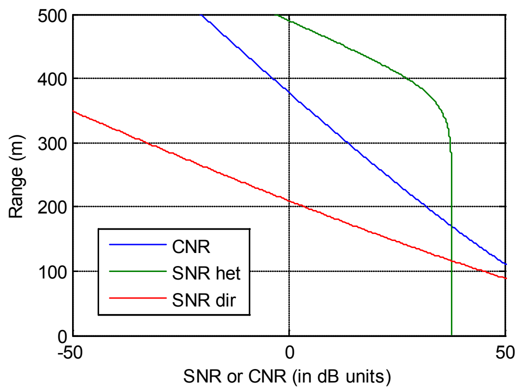

Figure 5: CNR (green) and SNR for a heterodyne (blue) and direct detection (red) lidar emitting 80mJ pulses at 10.6µm and a repetition rate of 10Hz, receiving light with a 10cm diameter telescope, and accumulating 6000 shots.

5. Signal processing.

The standard processing technique used for estimating the extinction coefficient from a lidar signal consists in computing the first order derivative the logarithm of the range-square corrected signal intensity $P(z)$:

$$\hat{\sigma}_{ext} = -\frac{1}{2}\frac{d}{dz}\ln\left(z^2 P(z)\right)$$

Simulations showed this estimator is biased at shirt distances due to the sharp decrease of $\beta(z)T^2(z)z^{-2}$ within the pulse volume. To illustrate this, let us assume the laser pulse is a square of length $L = 10m$, and $\beta = const$, $\sigma_{ext} \ll 1/L$. Then

$$P(z) = K\beta \int_{z-L}^{z} \frac{\exp(-2\sigma_{ext} z)}{x^2} dx$$

where K is a constant, and

$$\hat{\sigma}_{ext} \approx \sigma_{ext} + \frac{1}{2}\left[\frac{1}{z-L} - \frac{1}{z}\right] \approx \sigma_{ext} + \frac{L}{2z^2}$$

Figure 5 below shows the bias of the estimate for $\sigma_{ext} = 0.001m^{-1}$ (blue line) and the approximation (green dashes).

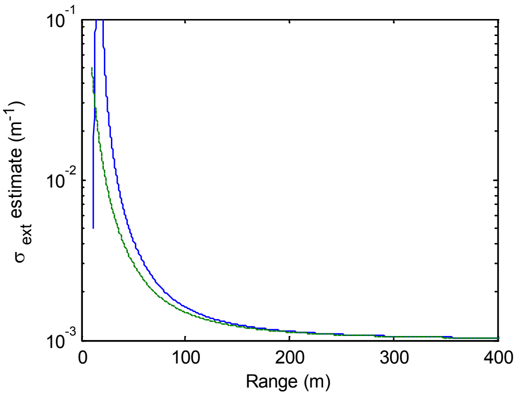

Figure 6: Estimate of the extinction coefficient within a fog characterized by $\beta = const$ and $\sigma_{ext} = 0.001m^{-1}$ (blue line) when the usual estimator (derivative of the logarithm of the range-square corrected signal) is used, A bias appears in the first hundreds of meters due to the sharp decrease of the signal within the pulse volume. It can be approximated (green dashes) by $\sigma_{ext} + L/(2z^2)$.

7. Conclusion

Observing fogs with lidars may at first glance seem an odd idea as the optical extinction of fogs is strong and does not allow for a deep penetration of the laser beam. However, fogs are thin, so deep penetrations are not necessary. The work conducted so far suggests heterodyne lidars could bring useful information on fogs. With powerful lidar systems; good CNR and SNR levels could be achieved as far as several hundred meters. The observation of the vertical structure of a fog throughout the whole depth of the atmosphere should thus feasible. As far as the LWC is concerned, the estimation of the optical extinction in the thermal IR seems to be a possible way to provide new and useful information to numerical prediction systems for the benefit of the quality of the predictions.

8. Acknowledgment

The work presented in this paper is supported by the French ministry of Defence.

9. References

1. Bergot T., and D. Guédalia, 1994: Numerical forecasting of radiation fog. Part 1: Numerical model and sensitivity tests. *Monthly Weather Review*, **122**, 1218-1230.

2. Bergot T, D. Carrer, J. Noilhan, and P. Bougeault, 2005: Improved site-specific numerical prediction of fog and low clouds: a feasibility study. *Weather and Forecasting*, **20**, 627-646.

3. Rémy S., and T. Bergot, 2009: Assessing the impact if observations on a local numerical fog prediction system. *Quarterly Journal of the Royal Meteorological Society*, **135**, 1248-1265.

4. Pinnick R. G., D. L. Hoihjelle, G. Fernandez, E. B. Stenmark, J. D. Lindberg and G. B. Hoidale, 1978: Vertical Structure in Atmospheric Fog and Haze and Its Effects on Visible and Infrared Extinction. *Journal of Atmospheric Sciences*, **35**, 2020 - 2032.

5. Pinnick R. G., S. G. Jennings, P. Chýlek, and H. J. Auvermann, 1979: Verification of a Linear Relation between IR Extinction, Absorption and Liquid Water Content of Fogs. *Journal of Atmospheric Sciences*, **36**, 1577 – 1586.