Observation with a lidar of the liquid water content in fog

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Introduction

- Fog and low level clouds are reducing capacity of airports:
  - At Roissy Charles-de-Gaulle airport (Paris), operations are subject to Low-Visibility-Procedures when the visibility is less than 2000ft and the cloud ceiling less than 200ft.
  - In LVP conditions, the capacity is reduced by a factor 2, causing costly delays and flight cancellations.
- Airport operators need reliable fog forecast a few hours in advance at least to optimize the traffic with the remaining capacity:
  - Give priority to long distance flights that have already taken-off,
  - Delay / cancel short distance flights (in Europe, many internal flights are less than 2 hours from their destination).

Heathrow flights cancelled because of thick fog

Thick fog disrupted flights at the UK's biggest airport today, with passengers experien delays and cancellations.

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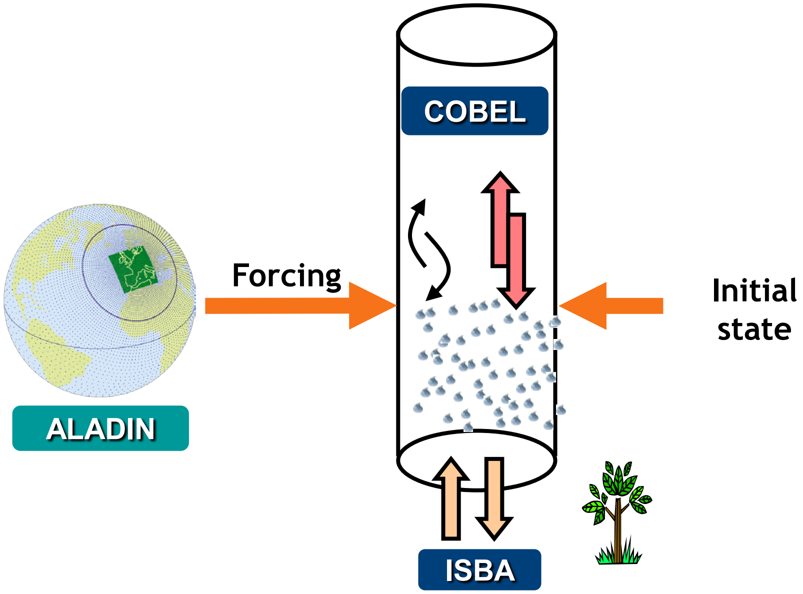
Numerical fog forecast

- Fog forecasts are provided to airport authorities
  - At Roissy CDG, a specific model COBEL-ISBA is run every hour and produces for forecasts for the next 12 hours.
  - COBEL-ISBA is 1D model with a fine vertical mesh for resolving the fine-scale processes involved in fog evolution.
- Prediction skills are limited:
  - Fine-scale non-linear processes,
  - Lack of real time observations (characterization of the initial state $X(t_0)$ of the atmosphere).
  - No observation of the vertical profile of the Liquid Water Content LWC critical for the prediction of fog dissipation.



$$\frac{dX}{dt} = F(X)$$

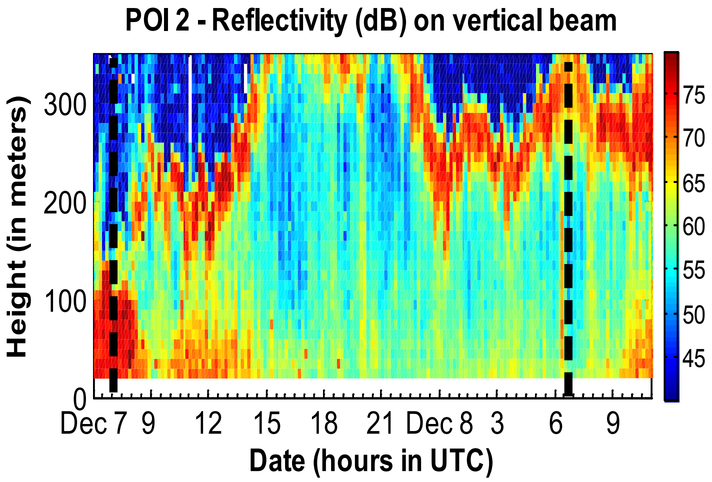
$$X(t) = X(t_0) + \int_{t_0}^{t} F(X(u))du$$

Specifications for LWC measurement

- Vertical resolution = a few tens of meters
- Time resolution = 10 minutes
- Accuracy = 10%

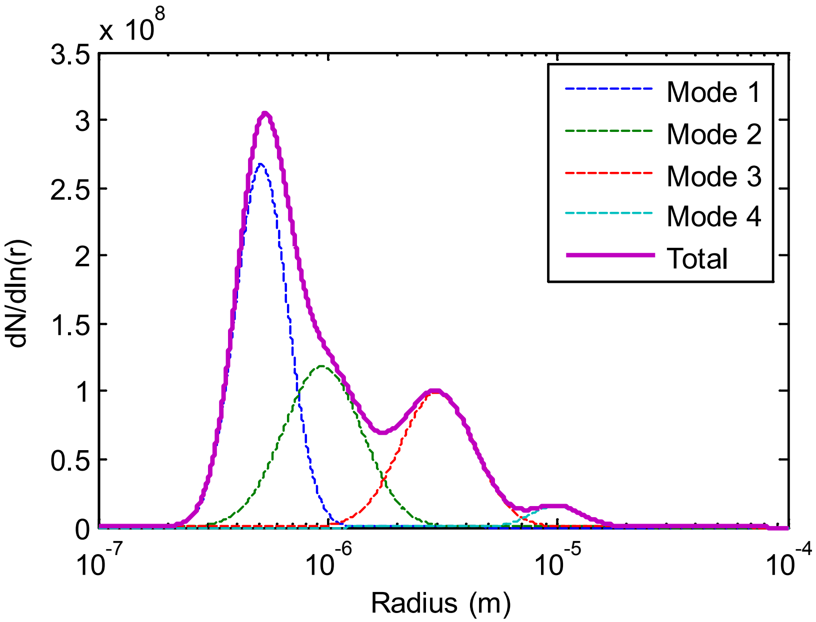
About fog

- Different types:
  - Radiative: cooling at the surface by IR emission → the temperature drops below dew point.
  - Descent of a stratus deck.
  - Advective: fog formed elsewhere and advected by the wind.
  - …
- Radiative fogs:
  - Prevail at Roissy CDG and many continental airports.
  - Formation in the late afternoon or during night (no solar heating).
  - Generally dissipates the next morning (solar heating).
  - Thickness: several tens to several hundred of meters.



Sodar echo as a function of height and time measured at Roissy CDG on the 7th and 8th of December 2008. The top of the fog layer is indicated by a line of strong reflectivity aloft.

Size distribution of water droplets



Size distribution modeled by the sum of “modes”:

$$\frac{dN_{tot}}{d\ln(r)} = \sum_k \frac{dN_k}{d\ln(r)}$$

where

$$\frac{dN_k}{d\ln(r)} = \frac{n_k}{\sqrt{2\pi}\sigma_k} \exp\left(-\frac{1}{2}\frac{\ln^2(r/r_k)}{\sigma_k^2}\right)$$

with r_k the “modal” radius and n_k the total concentration of the mode (number of drops by unit volume).

The modal radii are of the order of a micron or less (hence the low visibility), except for a mode of big drops of modal radius of 10µm or more. This mode does contain a small number of drops, but they contain a lot of water…

The large drops are difficult to measure with in-situ sensors… The precise characteristics of their mode is not fully known.

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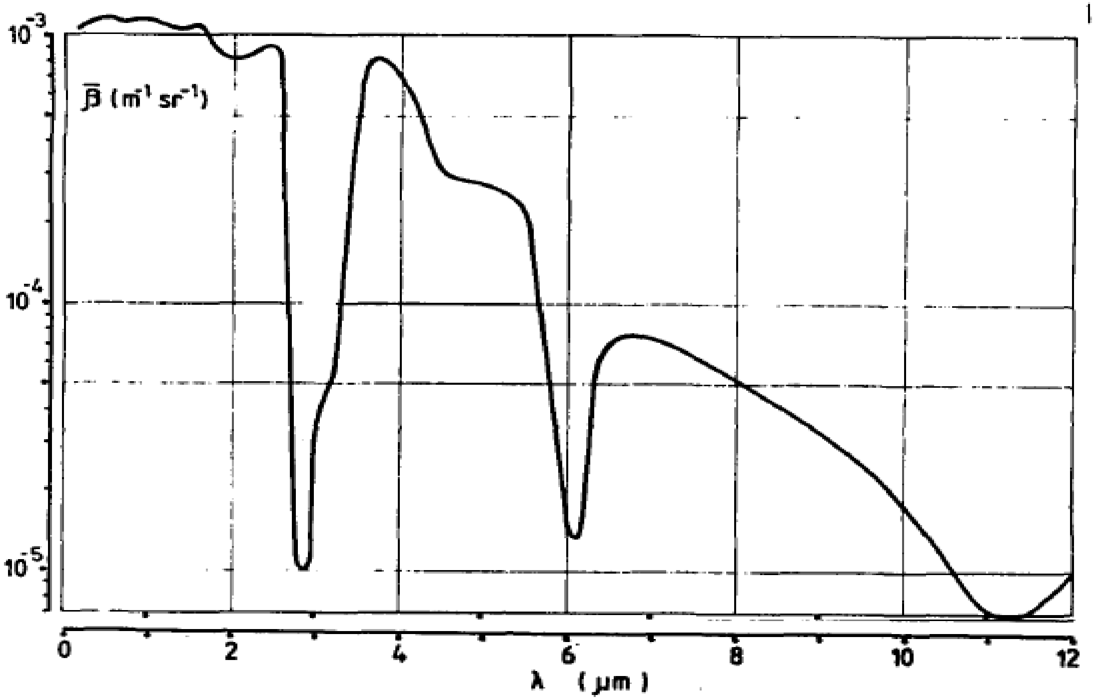
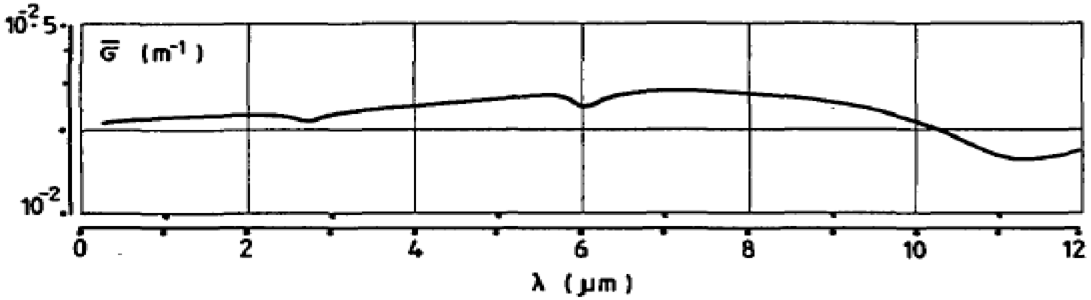
Optical properties



Average backscatter coeff:

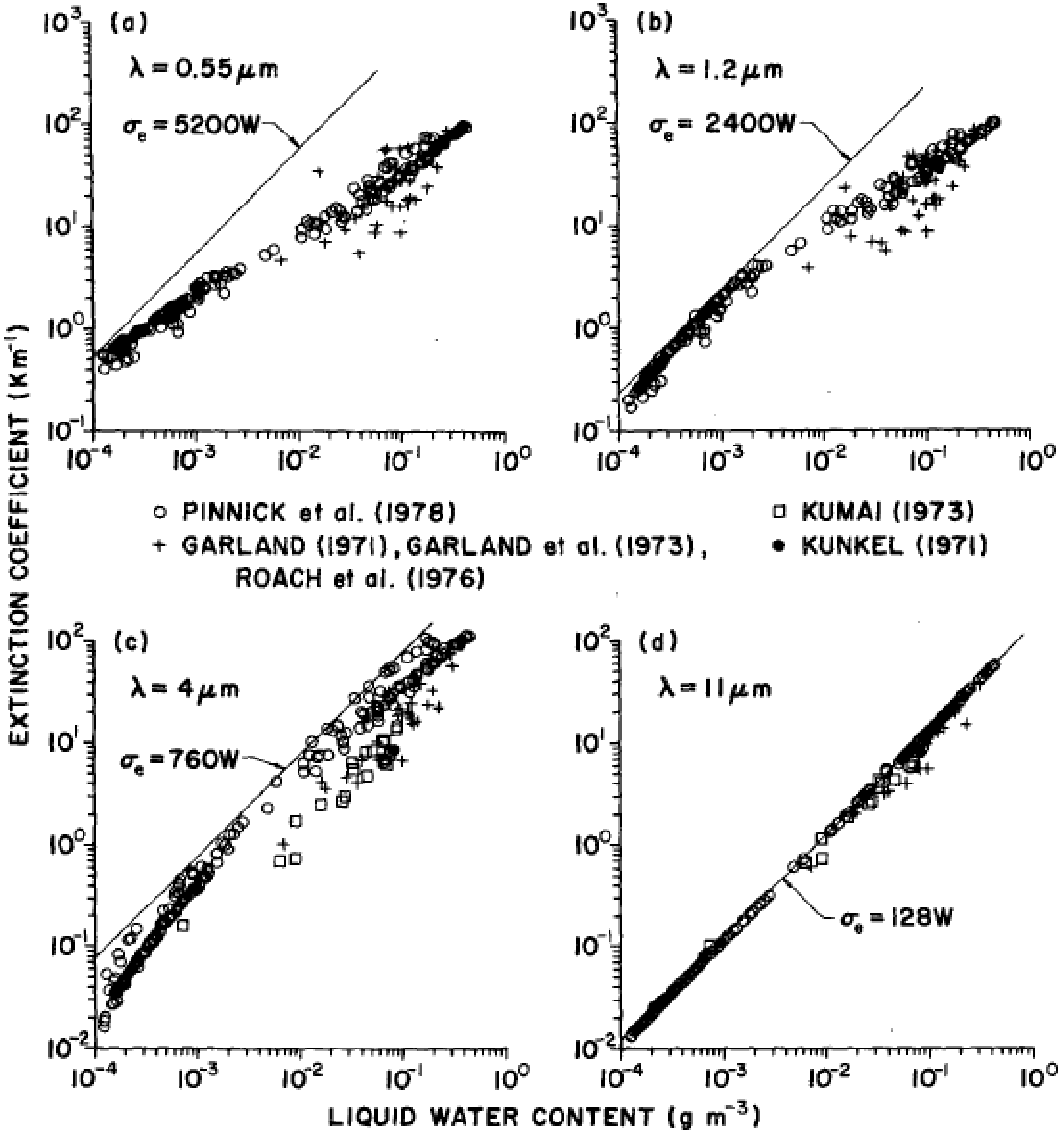
- ~10^{-3} m^{-1} sr^{-1} in the visible,
- ~2 10^{-5} m^{-1} sr^{-1} at 10µm.



Average extinction coefficient:
~ 2 10^{-2} m^{-1}

From G. Tonna, *Applied Optics*, **30**, 1132-1140, 1991

LWC versus Extinction



Extinction coefficient (at different wavelengths) versus LWC as measured in real fog cases.

From Pinnick *et al.*, 1979, *Journal of Atmospheric Sciences*, **36**, 1577-1586.

The graphs suggest there is a linear relationship between the extinction coefficient and the LWC for λ=11µm.

If true, the relationship can be used to measure the LWC with a lidar!

LWC versus Extinction

$$\mathrm{LWC} = \frac{4\pi\rho}{3}\int_{-\infty}^{+\infty} r^3 \frac{dN_{tot}}{d\ln(r)} d\ln(r)$$

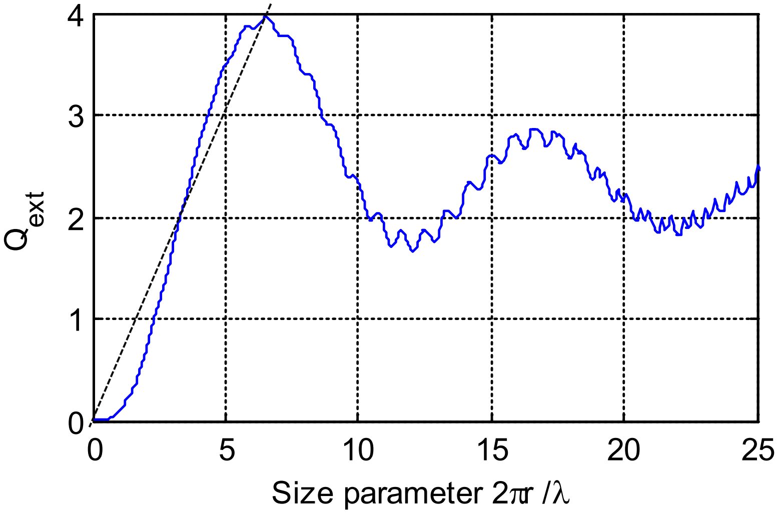
$$\sigma_{ext} = \pi\int_{-\infty}^{+\infty} r^2 Q_{ext}(2\pi r/\lambda)\frac{dN_{tot}}{d\ln(r)} d\ln(r)$$

If $Q_{ext}(x)$ can be approximated by

$$Q_{ext}\left(x = \frac{2\pi r}{\lambda}\right) \approx cx$$

for the particles in a fog, then

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



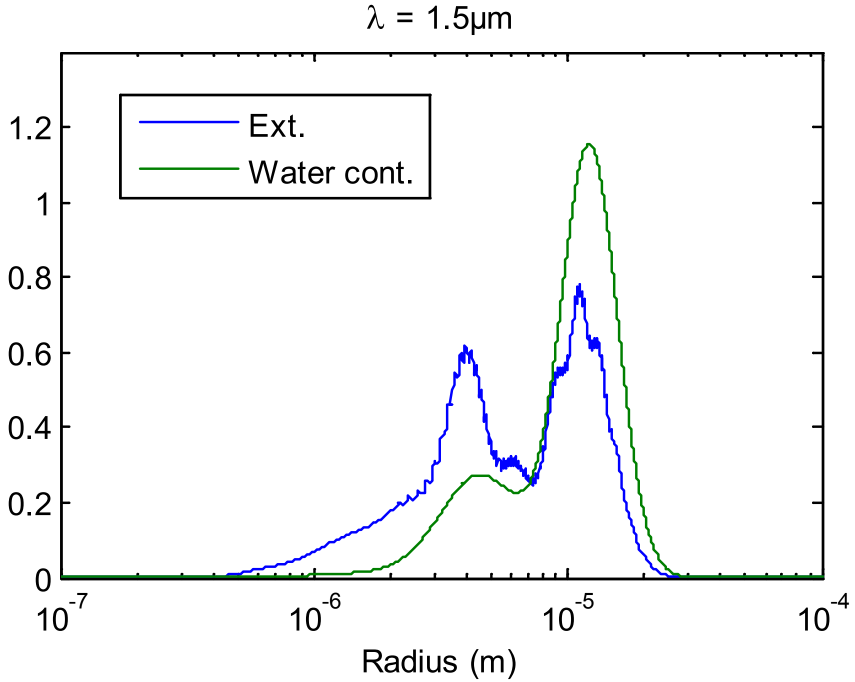
Extinction coefficient as a function of the size parameter x=2πr/λ. From Mie theory, with the refractive index of water at λ=10µm.

The approximation seems reasonable for x < 2π (or r < λ)
→ Long wavelengths are better for LWC retrievals.

LWC versus Extinction

Relative contribution of radius r to overall extinction.

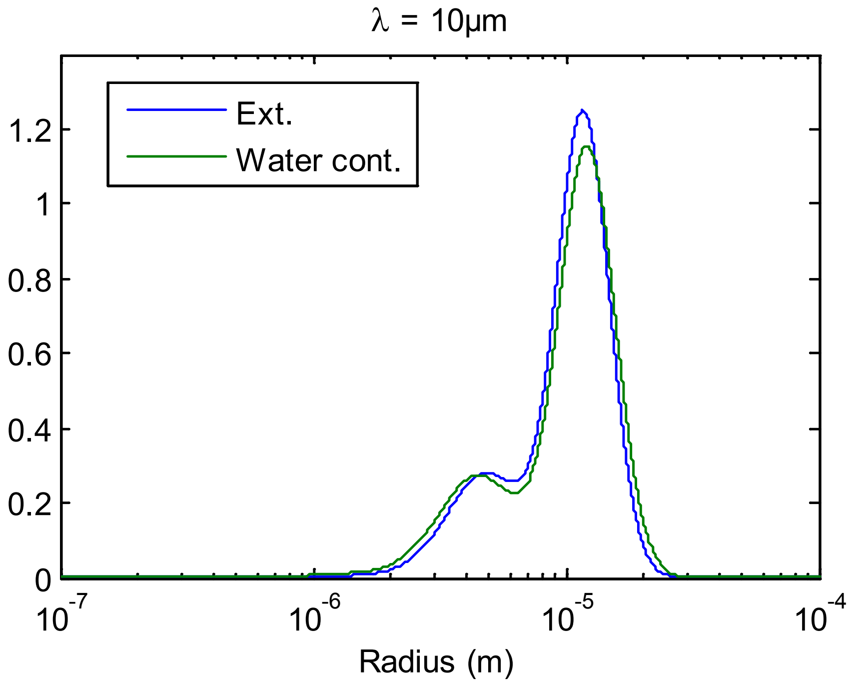
$$r^2 Q_{ext}(2\pi r/\lambda)\frac{dN_{tot}}{d\ln(r)} \Bigg/ \int_{-\infty}^{+\infty} r^2 Q_{ext}(2\pi r/\lambda)\frac{dN_{tot}}{d\ln(r)}\, d\ln(r)$$



λ = 1.5µm

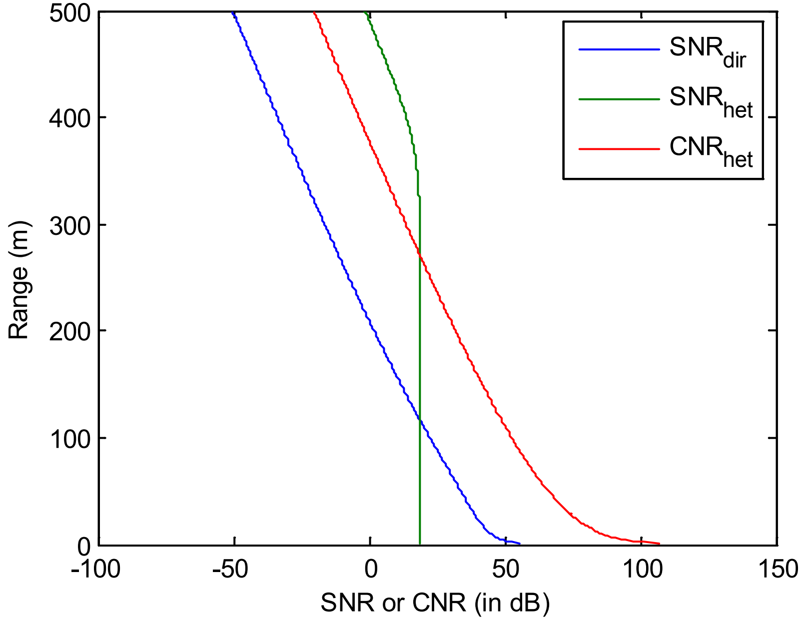
Relative contribution of radius r to overall LWC

$$r^3 \frac{dN_{tot}}{d\ln(r)} \Bigg/ \int_{-\infty}^{+\infty} r^3 \frac{dN_{tot}}{d\ln(r)}\, d\ln(r)$$



λ = 10µm

Selection of best detection scheme



Direct detection and heterodyne SNR as a function of range for a “big” 10,6µm lidar (80mJ/pulse, 10 pules/s, 10cm receiver diameter).

$$\boxed{SNR = \frac{P}{\sigma_P}}$$

Direct detection

$$SNR_{dir}^2 = \frac{1}{1+R_\lambda / P_s} \frac{qNP_s}{2h\nu B}$$

where N = number of shots (6000) and R_λ is the radiation from fog.

Heterodyne

$$SNR_{het}^2 = \frac{N}{1+2CNR_{het}^{-1} + CNR_{het}^{-2}}$$

$$CNR_{het} = \frac{q\gamma P_s}{2h\nu B}$$

Heterodyne detection reach longer ranges

Less sensitive to fog radiation

Estimation of extinction

Usual estimator for the extinction coefficient:

$$\hat{\sigma}_{ext} = -\frac{1}{2}\frac{d}{dr}\left[z^2\left(P(z) - P_{bg}\right)\right]$$

Let us assume that:

- The pulse is a square of length L (duration 2L/c)
- The backscatter coefficient β = const.
- The extinction coefficient σ_{ext} = const.
- The sensitivity is range independent.

Then

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

and, for $\sigma_{ext} << L^{-1}$

$$\hat{\sigma}_{ext} \approx \sigma_{ext} + \frac{L}{2z^2}$$

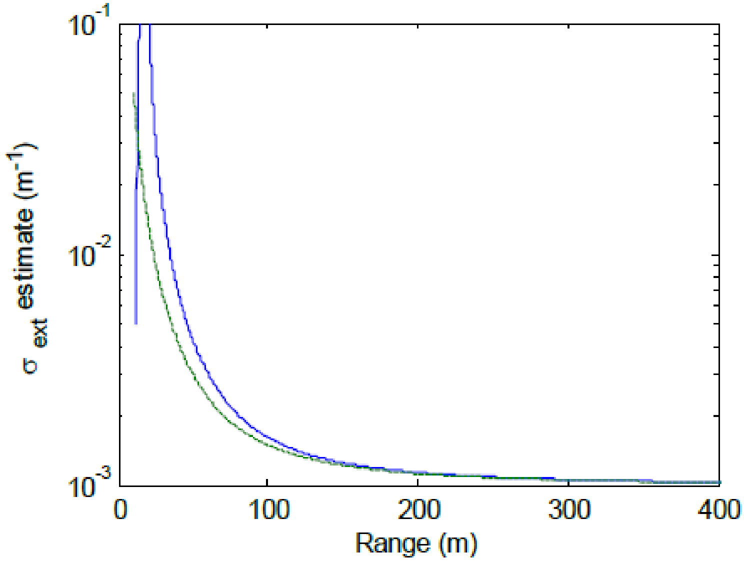


Figure 6: Estimate of the extinction coefficient within a fog characterized by $\beta = const$ and $\sigma_{ext} = 0.001m^{-1}$ (blue line) when the usual estimator (derivative of the logarithm of the range-square corrected signal) is used. A bias appears in the first hundreds of meters due to the sharp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

The estimator is biased due to pulse averaging…

Can be corrected, but requires a good calibration of the range dependant sensitivity of the system.

Conclusions

- In spite of the strong optical extinction, characterization of fog with a lidar does seem possible.
- The lidar could provide liquid water contents as a function of height that no other system provides today (measurement only available at the surface).
- Long wavelengths are more favorable.
- Direct detection inadequate → heterodyne detection (wind and wind turb. available).
- Several mJ, short pulse, and possibly high repetition rate lasers required.
- Future works: to conduct laboratory experiment s with a 10µm, 80mJ max, 10Hz lidar (from the old French-German airborne Doppler heterodyne lidar WIND).

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