IOSR Journal of Electronics and Communication Engineering (IOSR-JECE)
e-ISSN: 2278-2834,p- ISSN: 2278-8735.Volume 17, Issue 2, Ser. I (Mar. – Apr. 2022), PP 01-10
www.iosrjournals.org

Performance Analysis of Direct Detection and Heterodyne Detection Lidars for the Study of the Atmosphere

Marie Emile RANDRIANANDRASANA[1], Paul Auguste RANDRIAMITANTSOA[2], Andry Auguste RANDRIAMITANTSOA[3]
Department of Telecommunication, Antsirabe Vankinankaratra High Education Institute,
University of Antananarivo, Madagascar
Department of Telecommunication, High School Polytechnic of Antananarivo,
University of Antananarivo, Madagascar
Department of Telecommunication, High School Polytechnic of Antananarivo,
University of Antananarivo, Madagascar

Abstract**—** *Lidar is a laser-based remote measurement sensor that finds its best-known application in the study of the atmosphere. Our study on remote sensing by lidar system focuses on a few basic and fundamental principles on this one. Thus, included in this principle, it is necessary to know the type of detection that we should use for a defined study using lidars. The aim of this work is to start a study on the performance of lidar in direct detection and lidar in heterodyne detection.*

Keywords: *Lidar, direct detection, heterodyne detection, CNR*

Date of Submission: 25-03-2022 Date of Acceptance: 06-04-2022

I. INTRODUCTION

Atmospheric research nowadays is difficult to conceive without the use of remote sensing techniques. Laser remote sensing is an active area of research and is experiencing significant development in line with the growing needs for control and measurement for the environment. Currently, known as LIDAR (Light Detection And Ranging), this detection system using light has enormous advantages in the area of research that deals with the profiling of the atmosphere.

II. GENERAL PRINCIPLES OF THE LIDAR SYSTEM

2.1 Fundamentals of a Lidar

The lidar represents a remote sensing measurement tool operating on the same principle as a radar; it emits a pulse and the radiation backscattered by the targets or particles is analyzed in the field of view of the lidar in order to provide information on these sources of backscatter. The lidar uses a laser source that emits an electromagnetic pulse, almost monochromatic, whose emission wavelength can range from ultraviolet (about 0.2 µm) to infrared (about 10 µm).

The emitted laser beam is scattered by particles and molecules suspended in the air. The backscattered light is collected by a telescope. The signal is then picked up by a photosensitive detector coupled to an electronic signal analysis chain. These latter are spectrally filtered to minimize non-laser optical signals (especially the light from the sun), then they are scanned and saved according to the return time (propagation distance) for algorithmic extraction processing.

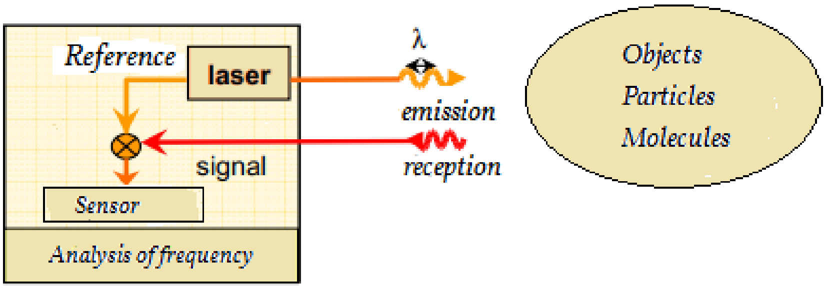

Figure 01. Diagram of lidar principle

2.2 Lidar equation

Assuming that the light energy has followed a straight path since its emission by the laser source until it is received by the telescope, the relationship between the duration of a round trip and the altitude of the scattering interaction at the origin of the energy return can be deduced through the speed of light: [1]

$$R = \frac{Ct}{2} \tag{1}$$

With :

- *R:* the distance in the direction of propagation [m],
- *C :* the speed of light [m/s],
- *t:* the time taken to make a round trip [s]

The backscattered optical power P(R) as a function of the distance R is called lidar signal and which is defined in its simplified form as follows:

$$P(R) = KG(R)\beta(R,\lambda)T^2(R,\lambda) \tag{2}$$

With :

- *K :* the performance factor of lidar system,
- *G(R) :* the geometric factor,
- $\beta(R,\lambda)$ *:* the backscattering coefficient [m^{-1}],
- $T^2(R,\lambda)$ *:* round-trip atmospheric transmission,
- λ *:* the wavelength in vacuum [m]

The first two factors *K* et *G(R)* depend only on the system and are therefore completely determined by the designer. The performance factor of the lidar system is expressed by:

$$K = \frac{C}{2} E_l A \eta_s \tag{3}$$

With:

- E_l : the energy of the laser pulse [J],
- A : the area of collecting optics [m^2],
- η_s : the system performance

The factor ½ is due to the fact that the laser pulse travels back and forth through the atmosphere.
The geometric factor is expressed as follows:

$$G(R) = \frac{O(R)}{R^2} \tag{4}$$

Where *O*(*R*) is the overlap factor of the field of view of the receiver and the laser beam.
Finally, the two other parameters β(R,λ) and T(R,λ) respectively reflect the quantity of light backscattered at a given altitude R and that lost on the round trip to the altitude R. Atmospheric transmission on the atmospheric layer going from an altitude from 0 m to R, has the expression: [2] [3]

$$T(R,\lambda) = \exp\left[-\int_0^R \alpha(z,\lambda)dz\right] \tag{5}$$

With :

- $\alpha(z,\lambda)$: the extinction coefficient [m^{-1}]
- z : the altitude [m]

Thus, the backscattered power equation can be expressed with the following equation:

$$P(R,\lambda) = \frac{C}{2} E_0 A \eta_s \frac{O(R)}{R^2} \beta(R,\lambda) \exp\left[-2\int_0^R \alpha(z,\lambda)dz\right] \tag{6}$$

With :

- E_0 : the laser energy [J]

2.3 Design Parameters

The designer of a lidar will seek to optimize the performance of his system according to many parameters that he will take care to assess as well as possible, and among which we can mention :

- The angular and spectral properties, in diffusion or reflection, of the target object.
- The spectral properties in transmission (absorption, diffusion, turbulence) of the propagation medium.
- The characteristics of the source: choice of wavelength, continuous emission or impulsive, frequency stability, etc…
- Choice of detection mode (direct or heterodyne) and type of processing of signal, depending on the information sought.

It should be noted that for a given mission, the optimization of system performance passes always by improving the signal-to-noise ratio at the output of the detector.

2.4 Measurement techniques

Critical lidar applications in areas such as defense (telemetry, guidance), space, atmospheric physics (atmosphere sounding, measurement wind speed), aeronautics (cable detection), these systems are above all required measurements of distances, speeds or angles.

The choice of a technique is dictated primarily by the nature of the parameter(s) sought, the specifications in measurement range and precision, the state of the art in the basic component, etc…and mainly concerns:

- The laser emission mode (continuous, pulsed),
- Beam modulation (in amplitude, frequency),
- The laser signal detection mode (direct, heterodyne)e)

2.5 Atmospheric lidars

The LASER beam is continuously diffused by particles and molecules of gas in the atmosphere (aerosols). This backscatter occurs throughout the propagation of the beam LASER. The measured parameters of the atmosphere can be:

- the speed of the air mass,
- air temperature,
- air density,
- the concentration of atmospheric gases,
- the load and nature of atmospheric aerosols and dust.

Among the atmospheric lidars, we distinguish the profiling atmospheric lidars (made with pulsed lasers), which provide the profile of a physical parameter along the line sighting, and localized atmospheric lidars (made with continuous lasers), which detects the signal from a specific and limited area of space (case studied here).

III. LIDAR DETECTION MODE

Concerning the lidar system, there are two detection modes:

- Lidar in direct or incoherent detection
- Lidar in heterodyne or coherent detection

3.1 Lidar in direct detection

The general principle of lidar in direct detection is summarized in Figure 02 below.

In direct detection, the backscatter of the laser beam by the target is directly collected and focused on a photodetector, which transforms the luminous flux received into electric current.Of therefore, all information about the phase of the laser wave is lost. [4] [5]

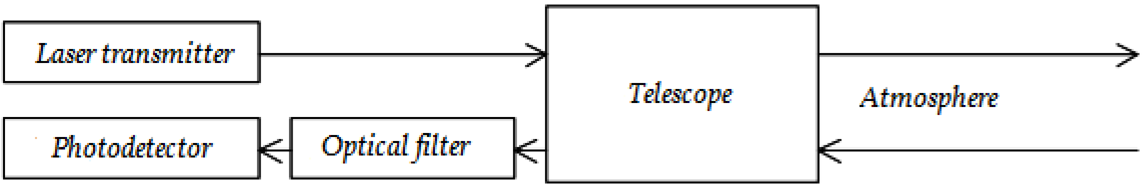

Figure 02: Schematic diagram of a lidar in direct detection

3.2 Lidar in heterodyne detection

The general principle of lidar in heterodyne detection is illustrated in Figure 03.

Heterodyning is a transposition technique in the radio frequency spectrum of a optical signal, which retains its amplitude and phase properties. In coherent or heterodyne detection, the radiation backscattered by the atmosphere, captured and focused by the telescope is mixed (or superimposed) with the beam of a continuous emission laser and stable in frequency thanks to a device called a local oscillator (LO). The detector produces then an electric current whose component measures the interference between the light backscattered and the local oscillator. This component is of alternating type, it beats at a frequency equal to that of the backscattered light minus that of the local oscillator. She falls in practice in the radio frequency range. [6] [7]

.

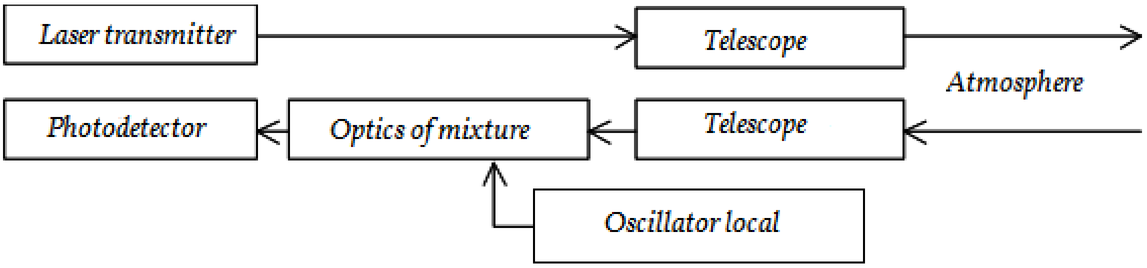

Figure 03 : Schematic diagram of a lidar in heterodyne detection

IV. PERFORMANCE STUDY FOR LIDARS WITH DIRECT DETECTION AND HETERODYNE DETECTION

4.1 CNR (Carrier to Noise Ratio)

In direct detection, the signal quality is characterized by the Carrier to Noise Ratio (CNR) whose expression in dB is: [8]

$$CNR = 10log_{10}\left(\frac{{i_s}^2}{{i_g}^2+{i_n}^2+{i_B}^2+{i_T}^2}\right) \tag{7}$$

With :

- ${i_s}^2$: the power received by the photodetector,
- ${i_g}^2$: the shot noise related to the backscattered signal,
- ${i_N}^2$: the shot noise related to the dark current of the photodetector,
- ${i_B}^2$: the shot noise related to the atmosphere,
- ${i_T}^2$: the Johnson noise (also called thermal noise) of the detector

It should be noted that the various noises entering into the calculation of the CNR being independent, their powers add up.

4.2 Noises

- ***Johnson noise***

This noise is generated by the thermal agitation of the charge carriers, the electrons, in a resistance in thermal equilibrium (here the load resistance of the photodetector).
He is therefore in function of temperature. Its expression is:

$${i_T}^2 = \frac{4k_BT_cB}{G_dR_c} \tag{8}$$

With :

- k_B : the Boltzmann's constant
- T_c : the temperature in Degrees Celsius
- B : the bandwidth
- R_c : the load resistance of the photodetector in Ohms
- G_d : the gain of the detector

- ***Noise related to the photodetector***

The dark current is the residual current of a photodetector in the absence of illumination.
This current induces shot noise on the photodetector signal. This noise has an expression typical shot noises:

$${i_n}^2 = 2eBi_N \tag{9}$$

With :

- e: the charge of the electron [C]
- i_N : the dark current of the photodetector [A]

- ***Backscattered signal noise***

The backscattered signal received by the photodetector also generates shot noise when its conversion into an electrical signal. The expression of this noise is that of a shot noise, like the one above, with the intensity iS of the lidar signal instead of the dark current of the photodetector: [9]

$${i_g}^2 = 2e^2B\eta_dP(t) \tag{10}$$

With :

- η_d : the quantum efficiency of the photodetector,

- $P(t)$: the backscattered power [photon.s^{-1}]

This previous power is expressed by:

$$P(t) = \frac{K_{opt}\lambda}{h}\beta(z)T^2(z)\frac{A}{2z^2}E_0 \tag{11}$$

With :

- K_{opt} : the coefficient of losses in the various optics

Then, the expression of the shot noise related to the backscattered signal is obtained using the expressions of lidar signal intensity and backscattered power and is expressed as follows:

$${i_g}^2 = e^2 B\eta_d \frac{K_{opt}\lambda A E_0}{hz^2}\ \beta(z)T^2(z) \tag{12}$$

- ***Atmospheric noise***

The shot noise related to the atmosphere can be written using the following expression:

$${i_B}^2 = \frac{4\pi e^2 B\eta_d CAD{\theta_t}^2}{\lambda^4}\frac{1}{e^{\frac{hC}{k_B T c\lambda}}-1} \tag{13}$$

With :

- D : the spectral width of the optical filter [m]
- θ_t : the field of view of the telescope [rad]
- ***Signal received by the photodetector***

The expression of the signal received in direct detection by the photodetector, used to calculate the carrier to noise ratio (CNR) is :

$${i_S}^2 = \frac{e\eta_d K_{opt}\lambda A E_0}{2hz^2}\ \beta(z)T^2(z) \tag{14}$$

4.3 Result in direct detection

Matlab software was used to calculate the CNR and plot its profile. The studied parameter is the range of the instrument. For this study, four steps are necessary, namely, the influence of the photodetector parameters, the influence of the telescope parameters, the influence of the other four instrumental parameters and the last step focuses on the influence of temperature.

- ***Influence of photodector parameters***

The different parameters of the photodetector influencing the noises and the received power studied previously are dark current, gain, load resistance and efficiency quantum. The CNR profiles corresponding to these parameters are illustrated in figure 04 below:

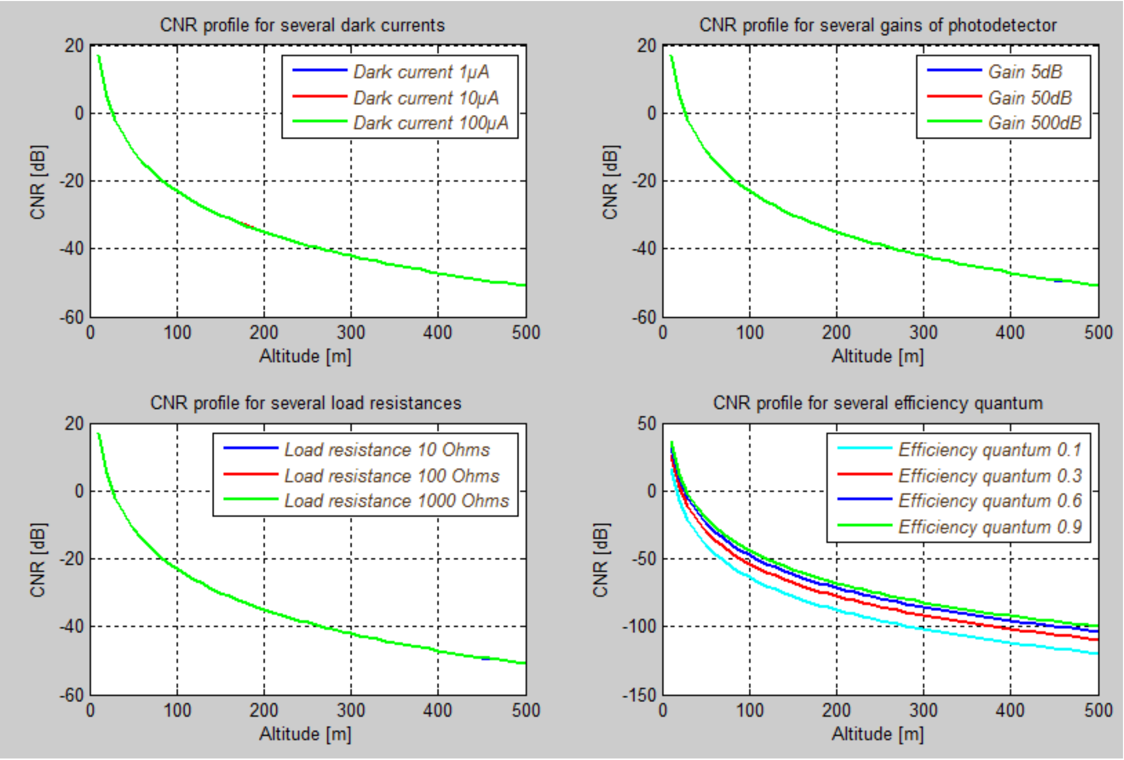

Figure 04: CNR profile with influence of the parameters of the photodetector

Note that with respect to two values of the CNR, the greater will be considered as the best and therefore it is the one that offers the best range with the parameters that match.
The dark current of the photodetector, the gain and the load resistance do not influence the value of the CNR while the quantum efficiency, being the only parameter, which influences it noticeably. The larger it is, the better the range of the instrument (Shown on the figure illustrating the CNR profile for several quantum yields).

- ***Influence of telescope parameters***

The surface and the field of view of the telescope are the parameters influencing the noises and the received power studied previously. Plots as a function of these two parameters have been made and can be found in Figure 05.

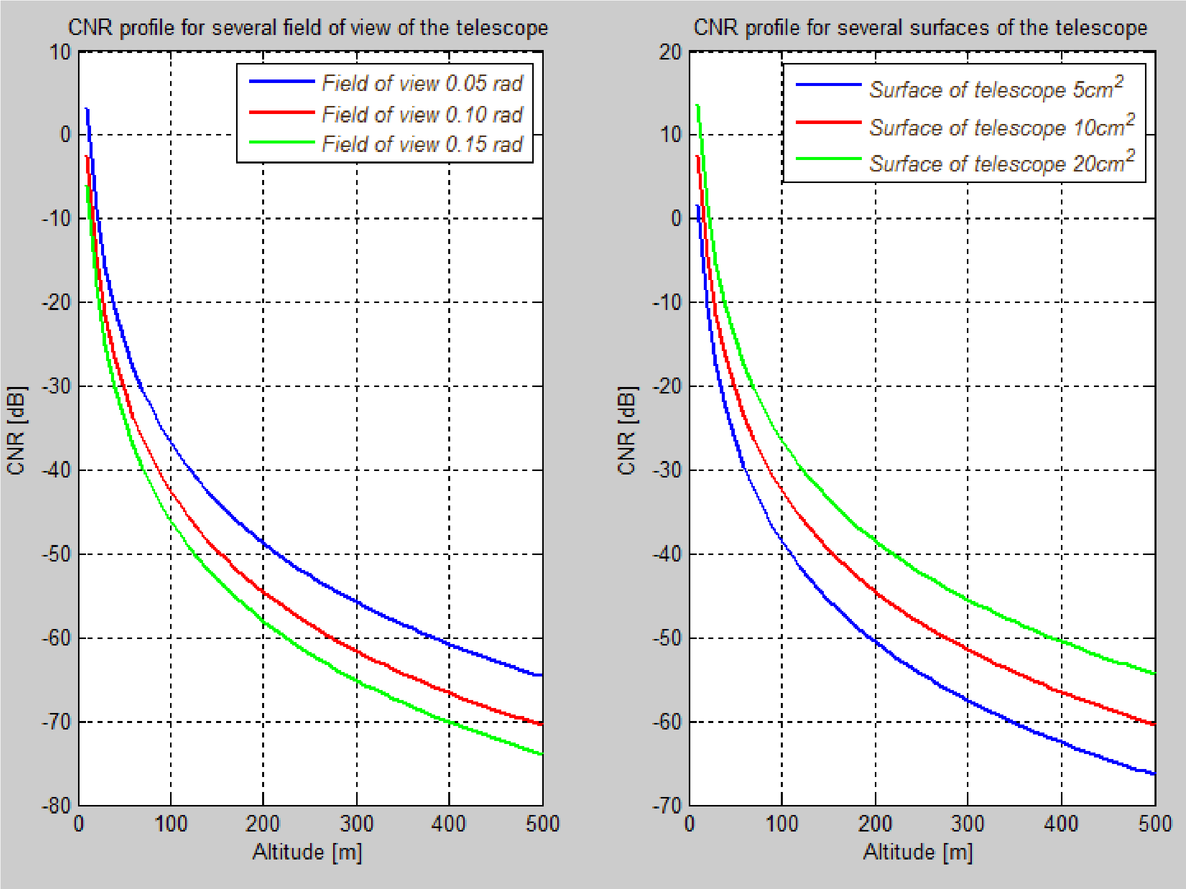

Figure 05 : CNR profile with influence of telescope parameters

Analyzing the figure above, the two telescope parameters influence the range of instrument, the telescope should be large with a narrow field of view to maximize range. These results are known for direct detection lidars. Note, however, that the narrowness of the field of view lengthens the size of the blind zone of the lidar when it is in configuration bistatic (the overlap between the field of view and the laser beam is done further), which, in our case, is detrimental since we seek to make measurements at short distances.
Moreover, neither of the two parameters has a significant impact on the range.

- ***Influence of other instrumental parameters***

In this paragraph, the study will be made of the influences on noise and on the power received studied previously of the spectral width of the optical filter, the bandwidth, the signal wavelength and laser energy. Variations in the value of the CNR in function of these four parameters are illustrated and can be found in Figure 06.

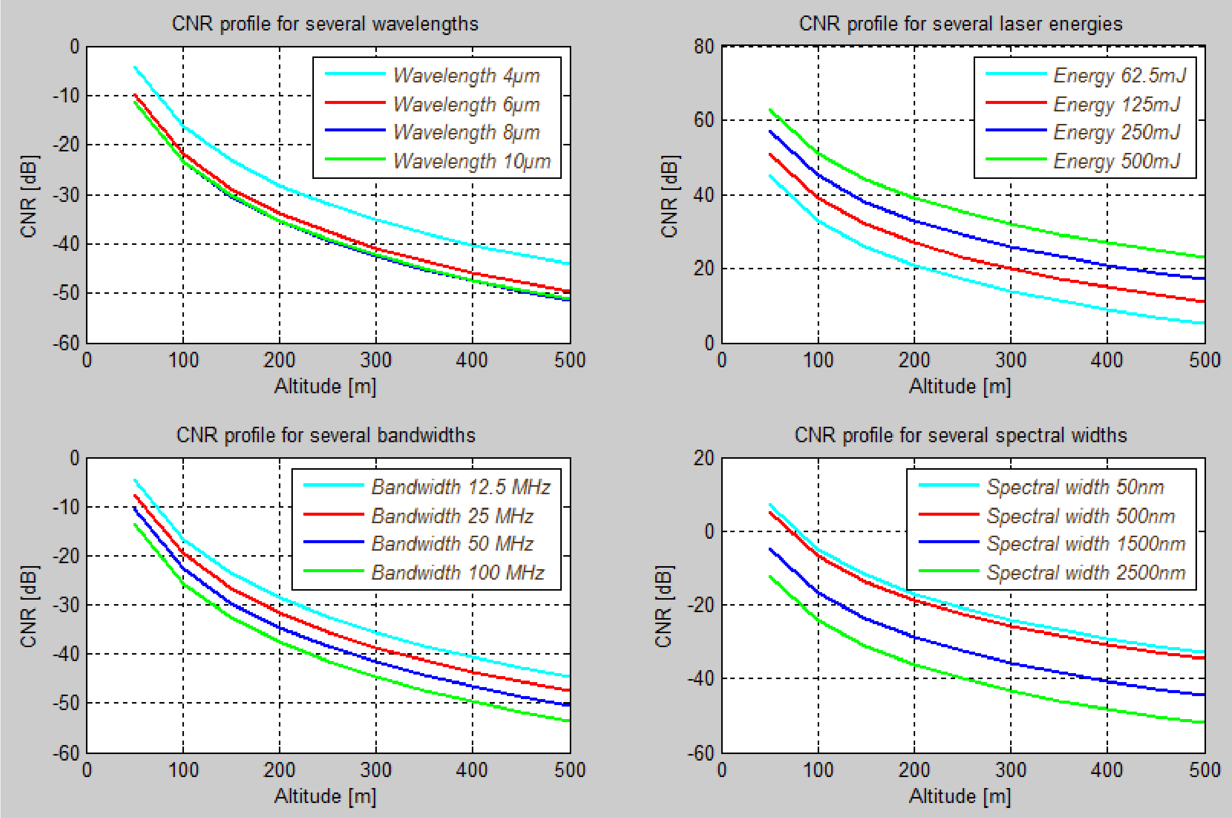

Figure 06: CNR profile with influences of instrumental parameters

Figure 06 shows us that the four parameters influence the range of the instrument. A bandwidth and narrow spectral width, and powerful laser provide better range to the instrument.
However, if the wavelength has a large impact, this is not the case for the others parameters. For 4µm, we have a better range compared to other wavelengths.

- ***Influence of atmospheric parameters***

Atmospheric parameters influencing noise and power received in direct detection previously studied are the temperature and the variation via the coefficient extinction and the backscattering coefficient of the particles present in the atmosphere by relative to the change in altitude (the particles in the atmosphere have their coefficients extinction and backscatter as one changes altitude). CNR profiles according to these parameters have been made and can be found in Figure 07.

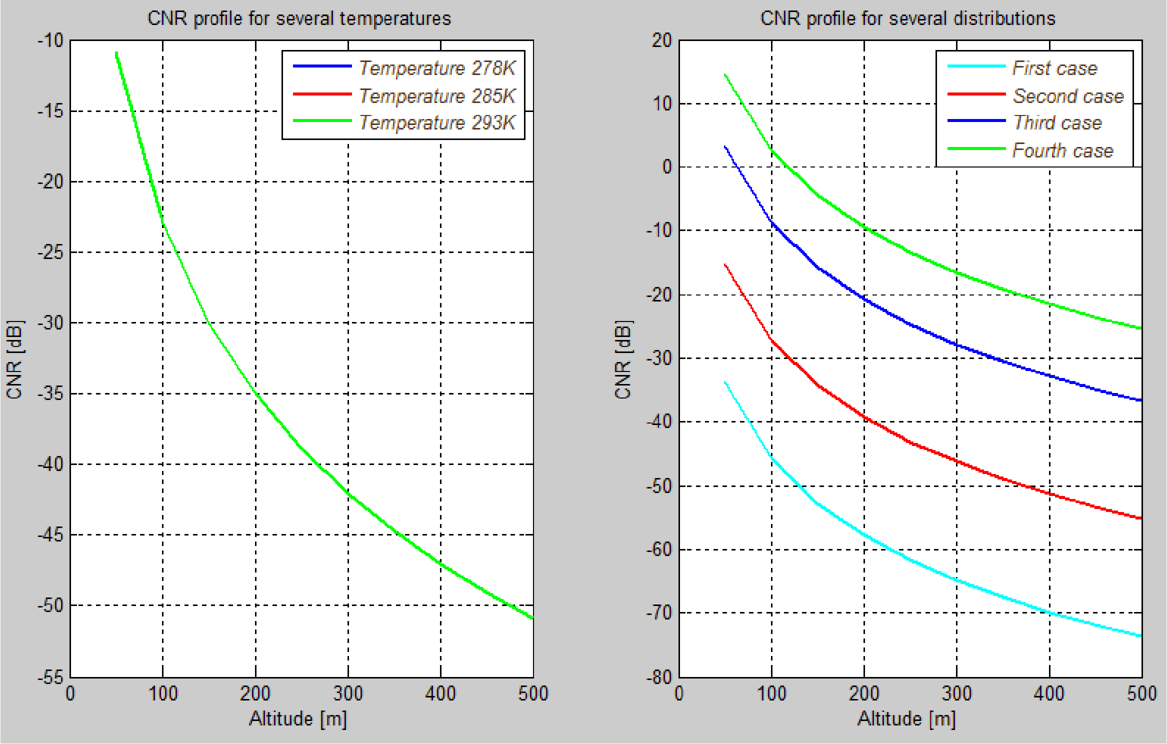

Figure 07: CNR profile with atmospheric influences

The temperature does not influence the range of the instrument while the variation of the value of the backscatter coefficient and extinction coefficient has a significant impact. Values of these are respectively: $\beta_1 = 3{,}09.10^{-8}[m^{-1}]$, $\beta_2 = 3{,}00.10^{-7}[m^{-1}]$, $\beta_3 = 2{,}50.10^{-6}[m^{-1}]$, $\beta_4 = 9{,}20.10^{-6}[m^{-1}]$, $\alpha_1 = 5{,}90.10^{-6}[m^{-1}]$, $\alpha_2 = 1{,}37.10^{-4}[m^{-1}]$, $\alpha_3 = 3{,}18.10^{-3}[m^{-1}]$ et $\alpha_4 = 1{,}54.10^{-2}[m^{-1}]$ for the four cases illustrated in the figure above.

4.4 Result in heterodyne detection

For lidar with heterodyne detection, the CNR (Carrier to Noise Ratio) is also studied to measure his capacity (or his incapacity). The CNR which is the ratio of the power average of the frequency modulated signal (the carrier) over the average noise power of detection (mainly linked to the shot noise of the local oscillator for a lidar well dimensioned). The CNR study makes it possible to know up to what altitude, the signal heterodyne has a sufficiently high power above the detection noise level so that it can be detected.

- ***Expression of the CNR***

CNR is the ratio of average heterodyne signal power to noise power at the detector. Its expression is:

$$CNR = \frac{<i_{het}{}^2>}{<i_b{}^2>} \tag{15}$$

With :

$$i_{het} = K_p \int_{S_D} \eta_d(r_d)|E_d(r_d,z_d)|^2\, dr_d \tag{16}$$

With :

- K_p : a proportionality coefficient,
- S_D : the area of the detector $[m^2]$,
- r_d : a current position on the detector,
- E_d : the detected wave,
- z_d : the coordinate of the following detector Oz and

$$< i_b{}^2 >= 2eBi_{dc} \tag{17}$$

With i_{dc} : the low frequency component of the current at the output of the detector.
For our study, we use another expression of the CNR [dB] mentioned below

$$NR = 10log_{10}\left(\frac{\eta_d\gamma}{2hB}K_{opt}E_0\lambda\beta(z)\frac{A}{2z^2}T^2(z)\right) \tag{18}$$

With :

- γ : the heterodyne efficiency (part of the direct detection power converted in heterodyne detection power)

- ***Influence of different parameters***

The bandwidth, the laser energy, the quantum efficiency of the photodetector, the surface of the telescope and wavelength are the parameters used to analyze lidar capacity as well as variations in the values of the backscatter coefficient and the coefficient of extinction. CNR profiles for different values of these parameters are shown by figure O8 below.

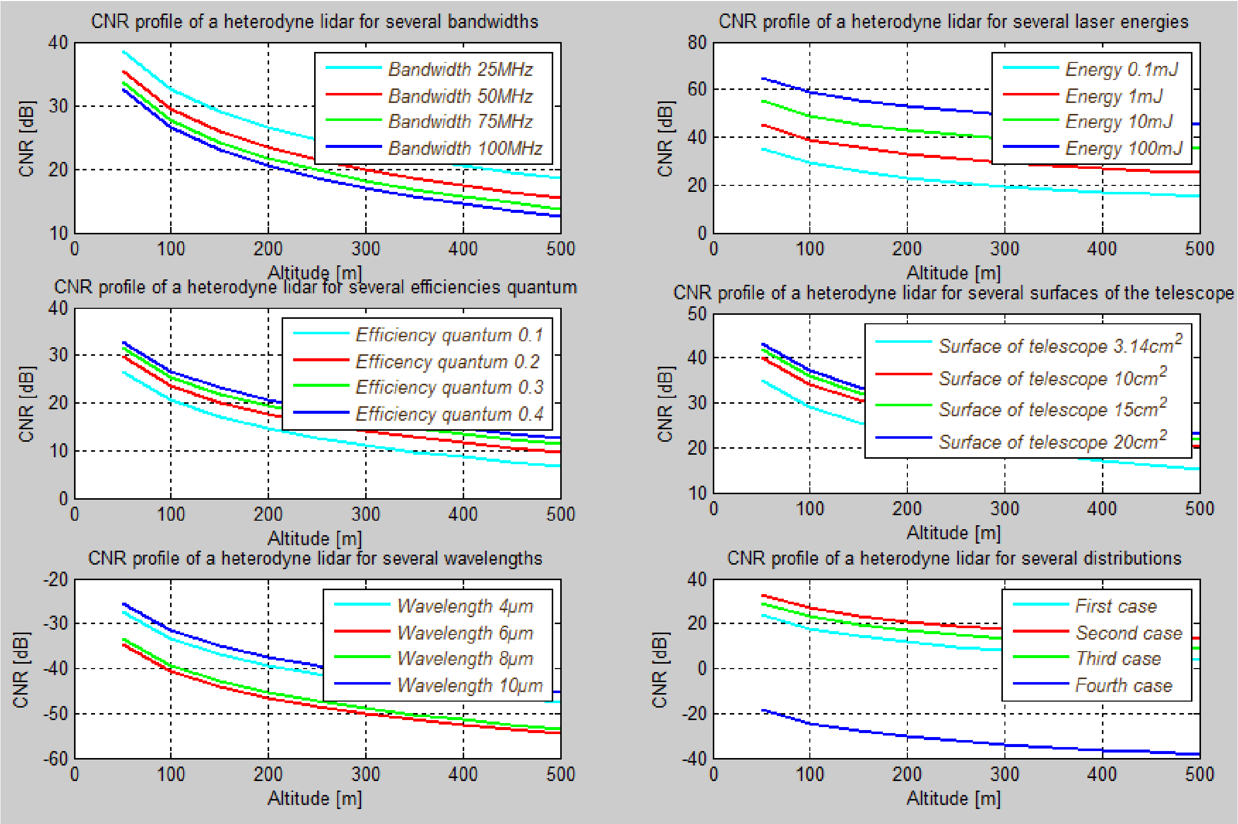

Figure 08: CNR profiles of a heterodyne lidar under the influence of different parameters bandwidth, energy of the laser, quantum efficiency of the photodetector, surface of the telescope, Wavelength, Variations of β and α

The range of the system is all the better as the energy of the laser is high. The yield Quantum also plays on range, but to a much lesser extent.

The bandwidth benefits from being refined, but we can see that its impact is quite limited. Note that in practice, it is a parameter on which we will not play much. We will avoid taking it unnecessarily large, but we will not try too hard to optimize it.

Focusing again on Figure 08, we can see that a telescope with a large lensoutput has a greater range. This result is consistent since the larger the telescope, the more signal it picks up.

About the wavelength, we also have a better range with that of 10µm. Similarly for the second case or else on the second variation of the backscattering coefficient and the extinction coefficient ($\beta_2 = 3{,}00.10^{-7}[m^{-1}]$, $\alpha_2 = 1{,}37.10^{-4}[m^{-1}]$), the scope seems also be better.

4.5 Comparison against the CNR of direct detection and heterodyne detection

To obtain an answer to the performance of the lidars to choose the type of detection for a determined application, the figure below shows the CNR profiles for the two detections suitable for lidar.

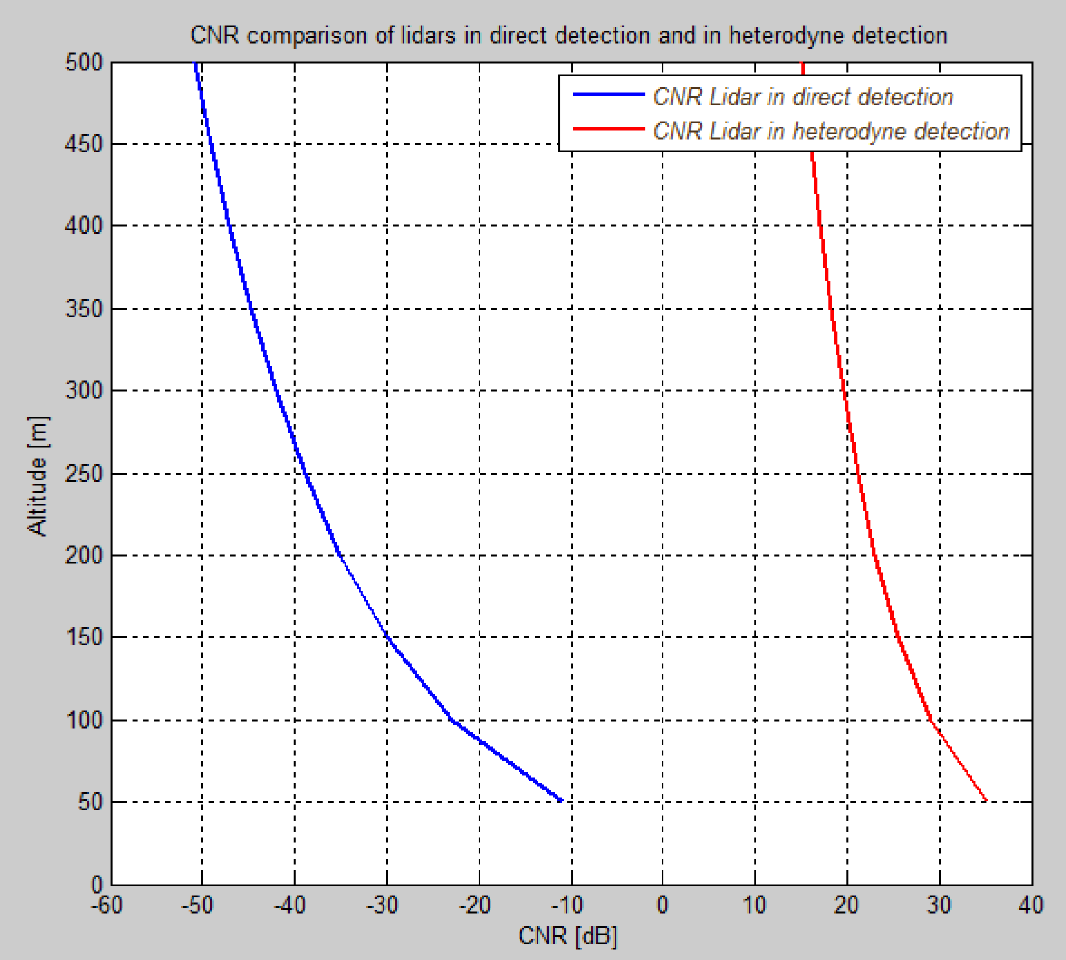

Figure 09 : CNR profile of lidar in direct detection and lidar in heterodyne detection

From what Figure 09 shows, the lidar CNR in heterodyne detection is worth more than that of lidar in direct detection, we can then affirm that heterodyne detection is the most appropriate compared to direct detection concerning the use of remote sensing by lidar.

However, this does not mean that direct detection lidars cannot be used for a defined atmospheric study, this type of lidar is limited by different parameters influencing the signal coming from the laser, but in terms of capacity and performance, heterodyne detection lidar seems to be the best.

V. CONCLUSION

This work is based on the study of the lidar system, also called optical radar. This system is a remote atmospheric sounding instrument, using electromagnetic waves optics. In terms of principle, the lidar uses two types of detection, namely the direct detection and heterodyne detection, that we have made short-range analyzes on their performance using the CNR (Carrier to Noise Ratio) parameter. Applied to different studies on the atmosphere, the lidar in heterodyne detection can satisfy scientists in the appropriate field to carry out a precise study such as the measurement of gases, particles or of the wind compared to the lidar in direct detection.

REFERENCES

[1]. Céline Klein, « Design and prototyping of a lidar for measuring water content liquid in the fog », 2013
[2]. Ulla Wandinger, « Introduction to Lidar », 2000
[3]. David Daon, « Characterization of aerosols by inversion of the combined data of solar photometers and ground lidars », 2012
[4]. Claudine Besson and Dolfi-Bouteyre, «Recent development in fiber lidar », 2013
[5]. JL Meyzonnette, « Laser radars », 1992
[6]. AI, « Coherent fiber lidar », 2009
[7]. Alexandre Baron, « Meteorological Raman lidar dedicated to the study of coupled cycles of aerosols and water vapour », 2020
[8]. Vincent DELAYE, « Study and production of a time-of-flight laser rangefinder », 2000
[9]. Jean-Pierre Cariou and Laurent Sauvage, « Atmospheric lidars », 2010