Lab work in photonics
Detectors and noise

Rooms	**B1**	**B2**	**B3**	**B4**
	S1.20	S1.15	S1.24	S1.28

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B 1

Photodetection noise sources

Prepare the question P1 before the session.

Contents

1 Objectives

At the end of this lab session, you are expected to be able to:

- differentiate between an offset (typically a dark current) and a noise;
- measure a noise amplitude, *i.e.* to be able to:
  - use an electrical spectrum analyzer;
  - convert quantities expressed in $\mathrm{dBm}_{@1\mathrm{Hz}}$ and in $\mathrm{W/Hz}$,
  - explain how the Spectrum Analyzer (SA) performs a measurement;
  - determine the influence of important parameters in any noise measurement, and in particular, the influence of the bandwidth (ENBW);
  - evaluate the uncertainty of the measurement;
- break down the different contributions (amplification noise, thermal noise, photon noise) to the total noise;
- propose a measurement method for each kind of noise;
- verify if a detection system is limited by photon noise;
- justify the term “photon noise”.

The objective of the first three parts of this lab is to study the main sources of noise present in any optical sensing system: the amplification noise, the thermal noise, and especially the photon noise.

The photon noise is related to the quantum nature of light. It has long been considered as a fundamental limitation. Under certain very particular conditions , it is nevertheless possible to fall below the photon noise limit, also known as the "standard quantum limit", as has been demonstrated for the first time in 1985 [1]. The last part presents an experiment that reduces the photon noise to a value below the standard quantum limit.

You are asked to fill up a table during the lab in order to record your measurements and verify their validity.

2 Measuring noise

2.1 Statistical approach

A noise is a random process. When measuring a noise, we want to determine its statistical properties, in particular its variance, also known as its rms value. By definition :

$$V_{rms}^2 = \int v^2 p(v) dv$$

where $p(v)$ is the density of probability of the process. It is not always known, but it can be estimated, experimentally measured.

2.2 Time-domain measurement

For all stationary and ergodic stochastic signals, we consider that the temporal statistical properties are the same as the ensemble statistical properties. This is the case for all kind of noise we will study here.

Therefore, with an oscilloscope, one can measure the Root Mean Square voltage V_{rms} of $v(t)$ (mean value is zero) defined by:

$$V_{\text{rms}}^2 = \lim_{T \longmapsto +\infty} \frac{1}{T} \int_{[T]} v^2(t) dt$$

This is the definition of the total power of a signal. This is also the temporal standard deviation for a noise:

$$V_{\text{rms}}^2 = \sigma_v^2 = \langle v^2(t) \rangle \quad \forall t$$

2.3 Frequency-domain measurement

The same RMS voltage measurement can be done in the frequency domain. With a spectrum analyzer (SA), we can measure the **Power Spectral Density** (PSD) of an electric signal. The

[1] Slusher *et al.*, Phys. Rev. Lett. **55**, 2409 (1985).

PSD is defined by:

$$\mathrm{PSD}(f) = \frac{1}{R_{\text{SA}}} \lim_{T \mapsto +\infty} \frac{2}{T} \left\langle \left| \widetilde{v_T}(f) \right|^2 \right\rangle \tag{1.1}$$

for frequencies $f > 0$. v_T is the signal $v(t)$, limited to the interval $[0\ T]$, $\widetilde{v_T}(f)$ is its Fourier Transform. R_{SA} is the input resistance of the SA. The PSD is expressed in $\mathrm{W/Hz}$.

The rms noise voltage, normalized at $1\,\mathrm{Hz}$, v_n (n for *noise),* is:

$$v_n(f) = \sqrt{R_{\text{SA}} \cdot \mathrm{PSD}(f)} \text{ in } \mathrm{V}/\sqrt{\mathrm{Hz}}.$$

We get the total power, so the RMS voltage by integrating the PSD over all frequencies :

$$V_{\text{eff}}^2 = R_{\text{SA}} \int_0^{+\infty} \mathrm{DSP}(f) df = \int_0^{+\infty} v_n^2(f)\, df$$

2.4 Link between the autocorrelation function of a noise and the PSD

Thanks to the Parseval theorem, we know that the total power of a signal does not depend on the representation (time or frequency) of the signal. There is a connection between those two, given by the Wiener-Khintchine theorem. The PSD can be obtained from the autocorrelation function $c_v(\tau) = \langle v(t)v(t-\tau) \rangle$ by a Fourier Transform :

$$\frac{2}{R_{\text{SA}}} c_v(\tau) \overset{\text{FT}}{\rightarrow} \mathrm{PSD}(f)$$

And for $\tau = 0$, thus leads to:

$$V_{\text{eff}}^2 = \sigma_v^2 = c_v(0) = R_{\text{SA}} \int_0^{+\infty} \mathrm{DSP}(f) df$$

2.5 White noise. Filtering.

The noises studied in this lab are very chaotic signals. There is no correlation between their value at time t and at time $t + \tau$. Their autocorrelation function, $c_v(\tau)$, is zero for all the values of τ except 0: $c_v(\tau) = 0$ except in $\tau = 0$. The PSD is then constant for all frequencies. By analogy with optics, the expression of "white noise" is used to characterize them. A white noise is a mathematical model. Its variance is infinite. We usually talk about white noise in a given bandwidth if the PSD is constant in this frequency bandwidth.

Furthermore, the measurement of a noise is always limited by a given bandwidth which can be the scope bandwidth, the resolution bandwidth of the spectrum analyzer, the bandwidth of a filter, ... The measured rms voltage is then :

$$V_{\text{eff}}^2 = \int_0^{\Delta f} v_n^2(f)\, df = v_n^2(f)\, \Delta f$$

where $v_n(f)$ is the rms noise voltage normalized at $1\,\mathrm{Hz}$, and is supposed to be constant in the bandwidth of analysis Δf.

So, measuring a noise consists in giving its rms voltage normalized at 1 Hz AND the bandwidth in which this power is measured !

Be aware that two noises may have the same PSD and very different time traces. An example of this is given on the figure 1.1 :

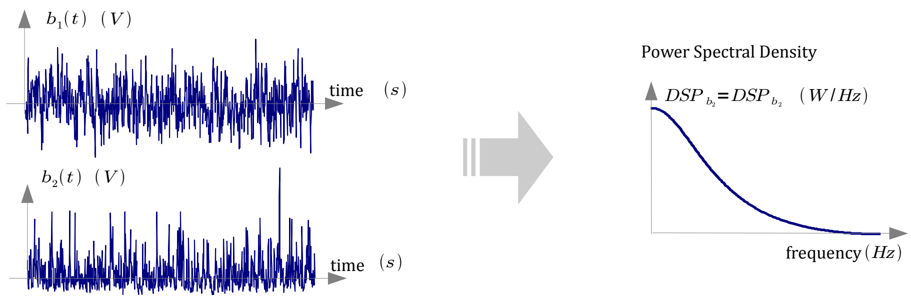


Figure 1.1: Two different noises with the same PSD.

P1 What is the shape of these two noise histograms? Are their autocorrelation functions identical ? Which one is a white noise? Which one is a Gaussian noise?

3 Amplification noise

We need a low-noise and high gain amplifier to measure the thermal noise of a resistance or the photon noise.

However, the amplifier produces its own noise. The aim of this part is to measure the amplifier noise.

This amplifier noise is the output noise of the complete electronic system, added to an amplified signal. Its rms value is noted $V_{\text{ampli,out}}$. In order to compare amplifiers with different gain and bandwidth values, the input rms noise voltage normalized at $1\,\text{Hz}$, is given. We consider then a noise generator at the input of an amplifier as shown in figure 1.2. We have to measure the rms noise voltage $v_{\text{n,ampli}}$ (in $\text{V}/\sqrt{\text{Hz}}$) of this white noise.

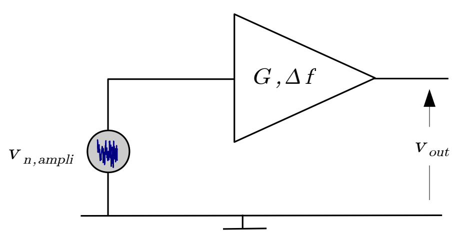


Figure 1.2: Input white noise model. G is the amplifier gain and Δf is its bandwith

The circuit diagram we will use is drawn on the figure 1.3: It corresponds to « Ampli 1 » aluminium box, with a grounded input. To shortcut the entrance, use the box of resistances connected directly to the Ampli 1 box input, and choose the $R = 0\,\Omega$ position. The amplifier is powered by batteries ($\pm 12\,\text{V}$) to avoid additional noise.

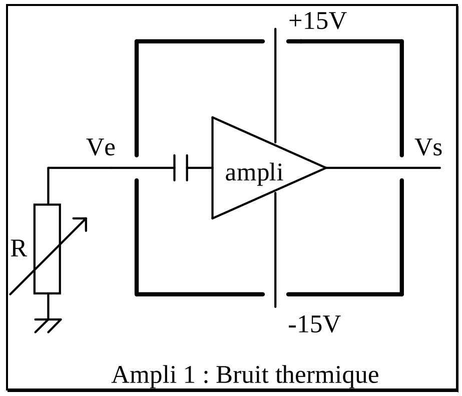


Figure 1.3: Amplifier noise and thermal noise measurements circuit.

3.1 Noise measurement with an oscilloscope.

⇝ Observe the output signal with the oscilloscope (1 or $2\,\mathrm{mV}$/division).

Q1 Observe the output voltage when you change the time scale. Does the shape of the noise seem compatible with a Gaussian white noise?

Q2 Measure approximately $V_{\text{peak to peak}}$ of the noise observed on the oscilloscope. Assuming this noise is a Gaussian noise, we know that : $V_{\text{peak to peak}} \approx 6V_{\text{RMS}}$. Deduce the Root Mean Square (RMS) value ($V_{\text{ampli, out}}$) of the amplifier output voltage. Using the value V_{RMS} calculated by the oscilloscope, check that the noise is indeed gaussian.

Furthermore we suppose that the amplifier gain is 300 and constant over a bandwidth of $\Delta f = 1,5\,\mathrm{MHz}$ (Bode Diagram in appendix)

Q3 What is the relationship between $v_{\text{n,ampli}}$ and $V_{\text{ampli,out}}$? Deduce from your measurement the rms input voltage noise of the amplifier $v_{\text{n,ampli}}$ and compare to the `AH0013` datasheet typical value: $v_{n,\text{AH1003}} = 2\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$

3.2 Noise measurement with a spectrum analyzer

With a spectrum analyzer (Tektronix 2712 for example), one can measure the PSD of the noise (scheme in appendix).

The SA displays the electric power of its input voltage in W or in dBm signal, dissipated in its input resistance $R_{\text{SA}} = 50\,\Omega$.

If this signal is a sine wave at frequency f_0 $v(t) = \sqrt{2}V_{\text{rms}} \sin(2\pi f_0 t + \phi)$, the displayed power is $P(f_0) = \frac{V_{\text{rms}}^2}{R_{\text{SA}}}$.

If this signal is periodic, the SA displays the power of each spectral component of the signal

If this signal is a noise, the SA displays the signal PSD, integrated over the resolution bandwidth $\delta f = \mathrm{RBW}$ around f_0:

$$P\left(f_0\right)=\frac{1}{R_{\mathrm{SA}}}\int_{f_0-\frac{\delta f}{2}}^{f_0+\frac{\delta f}{2}} v_n^2\left(f\right)\cdot df \text{ (in W)}$$

If we assume that the PSD is constant over δf :

$$P\left(f_0\right)=\frac{1}{R_{\mathrm{SA}}}\cdot v_n^2\left(f_0\right)\cdot \delta f \text{ (in W)}$$

Dividing this value by the resolution bandwidth, the SA measures the PSD (in $\mathrm{W/Hz}$) of the electrical signal :

$$\mathrm{PSD}\left(f_0\right)=P_{@1\,\mathrm{Hz}}\left(f_0\right)=\frac{v_n^2\left(f_0\right)}{R_{\mathrm{SA}}} \text{ (in W/Hz)}$$

Reminder: Remember that dBm is a logarithmic power unity. 'm' means that the reference is $1\,\mathrm{mW}$. A power in dBm is given by: $P_{\mathrm{dBm}}=10\log_{10}\left(\frac{P}{1\,\mathrm{mW}}\right)$ where P is expressed in mW. So, $0\mathrm{dBm}$ is $1\,\mathrm{mW}$, $-30\mathrm{dBm}$ is $1\,\mu\mathrm{W}$, $-60\mathrm{dBm}$ is $1\,\mathrm{nW}$, etc.
A PSD is given in $\mathrm{dBm}_{@1\,\mathrm{Hz}}$: $P_{@1\,\mathrm{Hz}\,,\,\mathrm{dBm}}=10\log\left(\frac{P_{@1\,\mathrm{Hz}}}{1\,\mathrm{mW}}\right)$

⇝ Connect the output of the amplifier to the spectrum analyzer input. Measure $P_{@1\,\mathrm{Hz}}\left(300\,\mathrm{kHz}\right)$ in dBm, the amplifier noise output power spectral density at $300\,\mathrm{kHz}$.

Q4 Using Excel, calculate the corresponding noise voltage, $v_{n,\mathrm{out}}(300\,\mathrm{kHz})$, at the amplifier output expressed in $\mathrm{V}/\sqrt{\mathrm{Hz}}$. The SA input resistance is $R_{\mathrm{SA}}=50\,\Omega$.

Q5 Determine the value of the amplifier gain at a frequency of $300\,\mathrm{kHz}$ from the Bode diagram of the amplifier given in Appendix. Deduce the rms input noise voltage $v_{n,\mathrm{ampli}}$. Compare it to the value obtained in the previous section and to the datasheet value for the low noise amplifier `AH0013`: $v_{n,\mathrm{AH1003}}=2\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$.

Q6 Observe the output noise voltage of the amplifier for a larger span of frequencies from 0 to $2\,\mathrm{MHz}$. Is it a white noise? Why? Compare to the Bode diagram (ampli Johnson noise) given in appendix. Explain why we can measure the Bode diagram of the amplifier by this method.

⇝ Check your calculations and your measurements with lab instructor.

4 Johnson noise (or thermal resistance noise)

With this amplifier it is easy to study the thermal noise (Johnson noise) of a resistance.

Voltage fluctuations across a resistor R at the absolute temperature T is a Gaussian white noise called thermal noise or Johnson noise. The rms noise voltage is given by the Johnson-Nyquist formula:

$$v_{n,R}=\sqrt{4\mathrm{k}TR}\text{ in } \mathrm{V}/\sqrt{\mathrm{Hz}},$$

where k is the Boltzmann constant: $\mathrm{k} = 1.380 \times 10^{-23}\,\mathrm{J.\,K^{-1}}$

A resistance can be replaced by a noiseless resistance R^* with a noise voltage generator of rms value $v_{n,R}$ as represented in the figure 1.4.

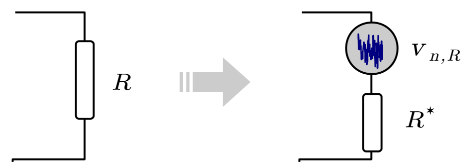


Figure 1.4: Resistance thermal noise model

The low noise amplifier studied previously can be used to study the thermal noise of a resistor connected between the amplifier input and ground.

4.1 Influence of the resistance

⇝ With the spectrum analyzer, measure $P_{@1\,\mathrm{Hz}}(300\,\mathrm{kHz})$ in dBm (output noise PSD at the frequency of $300\,\mathrm{kHz}$) for different resistors connected to the amplifier input.

Q7 Deduce the amplifier rms voltage output noise, $v_{n,\mathrm{out}}(300\,\mathrm{kHz})$, for these resistances (fill up the table started at question **Q4**).

At the entrance of the amplifier, we have two sources of noise,

– the amplifier noise, measured at question **Q5**,
– the resistance thermal noise.

We can represent these two noises by two white noise generators placed at the input of the amplifier (figure 1.5).

These sources are statistically independent. Therefore, the total noise power is the sum of the powers of these two noise generators.

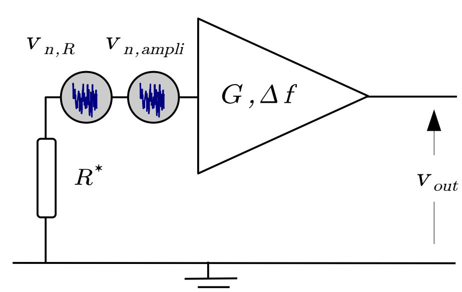


Figure 1.5: Model of the thermal noise of a resistance, at the input of a noisy amplifier.

Q8 With Excel, deduce from the previous measurements the rms noise voltage normalized at $1\,\mathrm{Hz}$, $v_{n,R}$ of the thermal noise for each resistance. Do not forget to take into account the noise of the amplifier.

Q9 Trace on the same graph the curves $v_{n,R} = f\left(\sqrt{R}\right)$ deduced from your measurements and from calculation using the Johnson-Nyquist formula.

Q10 Observe the noise voltage output of the amplifier for a larger frequency span from 0 to $2\,\mathrm{MHz}$ when you increase the value of R. Can you explain what you see? Deduce why the measured noise is different from the theoretical noise for the high resistance values.

Q11 Comparing the theoretical and experimental slopes for the small values of resistance, evaluate the systematic error measurement in $\mathrm{dBm/Hz}$ probably due to a calibration default of the spectrum analyzer.

Important To take into account and therefore correct this error later in the lab, keep the same settings of the spectrum analyzer.

4.2 Influence of the temperature

To measure the influence of the temperature, you will put a resistance (protected in a box) in liquid nitrogen and thus compare the noise at room temperature and at liquid nitrogen temperature. This simple experiment shows the principle of a noise thermometer by measuring the thermodynamic temperature.

⇝ Connect the resistance protected by a small metal box to the amplifier input.

Q12 Measure, using the spectrum analyzer, $P_{@1\,\mathrm{Hz}}\,(300\,\mathrm{kHz})$ in dBm, PSD of the output noise at a frequency of $300\,\mathrm{kHz}$, when the resistance is at room temperature. Deduce the rms noise voltage normalized at $1\,\mathrm{Hz}$, v_{n,R,T_1}. Do not forget to take into account the noise of the amplifier.

Q13 Repeat this measurement when the resistance is placed in liquid nitrogen. Deduce the rms noise voltage v_{n,R,T_2} at this temperature. Use this measurement to deduce the temperature of liquid nitrogen as accurately as possible.

5 Photon noise

The photon noise is related to the statistical fluctuations of the photons collected by the photodetector. The photon counting statistics is known to be Poissonian: if the detector surface receives N photons in average during an integration time τ, the standard deviation of the number of photons received is $\sqrt{N}$.

The photoelectrons created in the detector obey the same Poissonian statistics and this explains the shot-noise (often called photon noise) on the photocurrent. The average photocurrent is I_{ph} and the variance $i^2_{n,\mathrm{ph}}$ of the fluctuations is given by the Schottky formula:

$$i_{n,\mathrm{ph}} = \sqrt{2\mathrm{e}I_{\mathrm{ph}}}\ (\text{in } \mathrm{A}/\sqrt{\mathrm{Hz}})\ \text{where } \mathrm{e} \text{ is the electron charge } \mathrm{e} = 1.6 \times 10^{-19}\,\mathrm{C}$$

A photodiode (detecting a Poissonian flux of photons) can be represented by a DC current generator I_{ph}, in parallel with a current noise generator:

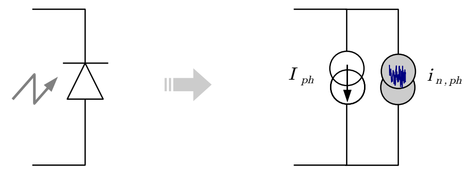


Figure 1.6: Photodetection noise model.

This current noise will be amplified by the circuit of the figure 1.7 :

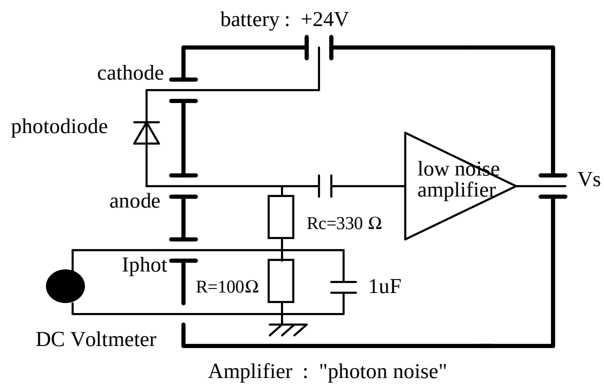


Figure 1.7: Amplifier : "photon noise"

The DC component of the current I_{ph} passes through the two resistances R_1 and R_2. We can deduce its value from the measurement of the voltage V across R_2 $(100\,\Omega)$: $I_{\text{ph}} = V/R_2$. The photodiode is reverse biased with $24\,\text{V}$ DC supplied by a battery (noiseless).

⇝ Connect the photodiode and the battery. Place the photodiode in front of a white light source which intensity is adjustable. The photodiode is an E.G.G. `C30809` photodiode whose quantum efficiency is 0.83 at $900\,\text{nm}$ (datasheet in appendix).

A voltmeter connected to the output `Iphot` of the box measures the DC photonic current delivered by the photodiode.

⇝ Check the average photocurrent increases with the flux received by the photodiode (do not go above $10\,\text{mA}$, $1\,\text{V}$ on the voltmeter).

⇝ Observe the noise output voltage of the amplifier using the oscilloscope and the spectrum analyzer when increasing the flux.

Q14 Observe the output noise for a span from 0 to $2\,\text{MHz}$. Is the shot noise a white noise? How is it varying with the flux received by the photodiode?

Q15 Measure, using the spectrum analyzer, $P_{@1\,\mathrm{Hz}}\,(300\,\mathrm{kHz})$ in dBm, PSD of the output noise at a frequency of $300\,\mathrm{kHz}$, for different average photocurrents I_{ph} from 0 to $10\,\mathrm{mA}$. Deduce the rms noise voltage $v_{n,\mathrm{out}}(300\,\mathrm{kHz})$ for these values of I_{ph}.

At the entrance of the amplifier, we have now three sources of noise:

– the photon noise $v_{n,\mathrm{ph}} = R_1 \cdot i_{n,\mathrm{ph}}$,
– the resistance $(R_1 = 324\,\Omega)$ thermal noise, v_{n,R_1},
– and the amplifier noise, $v_{n,\mathrm{ampli}}$.

Note that the R_2 resistance is not taken into account here because it is short-circuited by the capacitor in parallel. The complete noise model of the photodetection is given by the circuit in Figure 1.8:

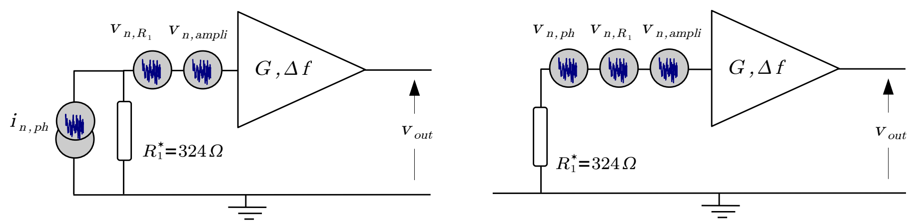


Figure 1.8: Photodectection noise model.

These noise sources are statistically independent. So their noise powers can be summed in order to find the total noise power:

$$v_{n,\mathrm{tot}}^2 = v_{n,R_1}^2 + (R_1 \cdot i_{n,\mathrm{ph}})^2 + v_{n,\mathrm{ampli}}^2 \; (v_{n,\mathrm{tot}} \text{ in } \mathrm{V}/\sqrt{\mathrm{Hz}})$$

The noise measurement when $I_{\mathrm{ph}} = 0\,\mathrm{mA}$ gives the measurement of the amplifier and thermal noises.

Q16 Determine the value of the amplifier gain at a frequency of $300\,\mathrm{kHz}$ from the Bode diagram of the amplifier given in Appendix, deduce the voltage noise at the input of the amplifier: $v_{n,\mathrm{tot}}$.

Q17 With Excel, calculate the rms noise current $i_{n,\mathrm{ph}}$ taking into account the systematic error determined in question **Q11**.

Q18 Plot: $i_{n,\mathrm{ph}} = f\left(\sqrt{I_{\mathrm{ph}}}\right)$. Compare with the values given by the Shottky formula.

⇝ Check your calculations and your measurements with the lab instructor.

6 Noise reduction

This last part presents a way to measure a photocurrent with a noise power below the shot-noise limit. This experiment will prove that the photodetector is not responsible for the shot-noise. Shot-noise is related to the quantum nature of light and the shot-noise limit is due to the Poissonian statistics of the collected photons. This experiment will show that a suitable light source can give a sub-Poissonian statistics of photons collected and consequently leads to a reduction of noise.

The idea is here to use, as a light source, a high quantum efficiency light-emitting diode (Hamamatsu `L2656` whose quantum efficiency is about 0.15 photons per electron at center wavelength of $890\,\mathrm{nm}$). We put this LED as close as possible to the photodiode (`E.G.G. C30809`) to collect the largest number of photons we can (we took off the window of the photodiode, and both the LED and the photodiode are in a metal box).

The figure below explains the principle of the shot-noise reduction experiment:

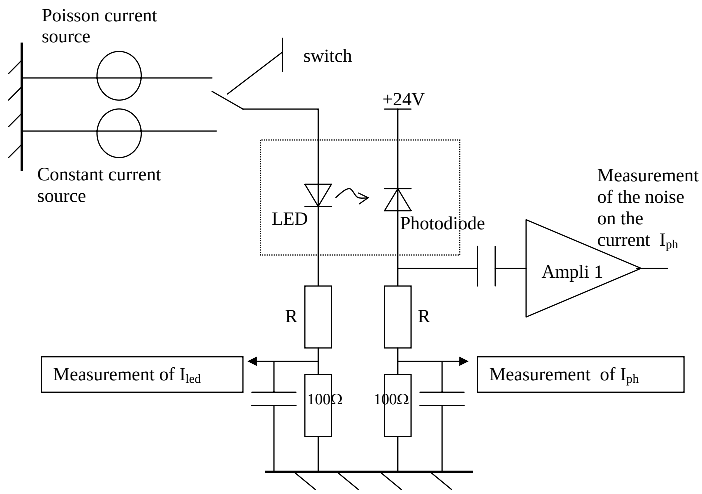


Figure 1.9: Principle of the shot-noise reduction experiment

Figure 1.10 represents the circuit which drives the LED either with a very low noise current produced by an usual stabilized power supply (`KIKUSUI`) or with a "Poissonian" current produced by three photodiodes illuminated by an ordinary white light source. Changing the light level will change the mean current through the LED. It is easy to adjust the stabilized power supply and the light level in a way to get exactly the same mean current in the LED. This current, I_{LED} , is measured by a voltmeter in parallel with the $300\,\Omega$ resistance.

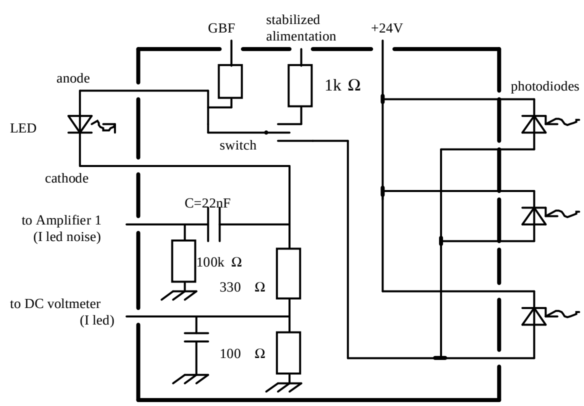


Figure 1.10: Setup of the sub-Poissonian/Poissonian light emitting device

6.1 Connecting the circuit

⇝ Replace the photodiode of the previous part by the photodiode which is in the small box "photodiode + LED".

⇝ Connect a second voltmeter at the `ILED` output to measure the average current in the LED. Connect the stabilized power supply and the bias voltage polarization for the 3 photodiodes ($24\,\mathrm{V}$) to the commutation box. Do not connect anything to the input "`GBF`".

⇝ Put the switch on the "stabilized power supply" position and adjust the photocurrent in the photodiode at exactly $3\,\mathrm{mA}$.

⇝ Put the switch on the "Poisson current" position, and adjust the flux on the 3 photodiodes in order to get the exactly same photocurrent ($3\,\mathrm{mA}$) in the photodiode.

6.2 Measurement

Q19 Measure the current in the LED and deduce the total quantum efficiency η_T, *i.e.* the number of electrons delivered by the photodiode per second divided by the number of electrons crossing the LED per second.

Q20 With the spectrum analyzer, measure $P_{@1\,\mathrm{Hz}}\,(300\,\mathrm{kHz})$ in dBm. Check that you find exactly the same value as in the previous part (**Q15**). This proves you are at the shot noise level.

Q21 Deduce the rms noise current $i_{n,\mathrm{ph}}$.

⇝ Switch to the "stabilized power supply"position. Check that the DC current is still $I_{\mathrm{ph}} = 3\,\mathrm{mA}$.

Q22 Measure $P_{@1\,\mathrm{Hz}}\,(300\,\mathrm{kHz})$ in dBm. Deduce the rms noise current $i_{n,\mathrm{ph}}$.

Q23 What noise reduction (in dB) do you find?

Q24 Compare to the value calculated as explained in the next paragraph.

To obtain a better visualization of the noise reduction, you can display the spectrum on $5\mathrm{dB}$/div scale. Then you can average the spectrum on the "Poissonian current" position and save it. At last, average the spectrum on "stabilized power supply" position and save it.

⇝ Ask the lab instructor how to use the average function of the spectrum analyzer.

6.3 Simple explanation of the noise reduction

When a constant current source is used to drive the LED, the noise on the current is very low. The fluctuations of the number of electrons crossing the LED are very low in comparison with a "Poissonian statistics". If the quantum-efficiency of the LED was equal to one, the fluctuations of the number of photons emitted by the LED and collected by the photodiode would be very low too. The resulting noise reduction would be very large.

Unfortunately, the total quantum efficiency, $\eta_T = \eta_{\text{PhD}} \cdot \eta_{\text{LED}}$, is only about 0.17. This means that for six electrons crossing the LED only one electron on average will be generated by the photodiode.

If we suppose that the current in the LED is noiseless, the number of electrons through the LED, $N_{e,\text{LED}}$, during a time τ, is constant. The number of electrons generated by the photodiode during a time τ is thus given by a binomial distribution. The mean value and the variance of the number of electrons crossing the photodiode during a time τ are:

$$\overline{N_{e,\text{photodiode}}} = \eta_T N_{e,\text{LED}}$$

and:

$$\sigma_{N_{e,\text{photodiode}}} = \sqrt{\eta_T \left(1 - \eta_T\right) N_{e,\text{LED}}}$$

This leads to:

$$I_{\text{ph}} = \frac{\overline{N_{e,\text{photodiode}}}}{\tau}\text{e} = \eta_T \frac{\overline{N_{e,\text{LED}}}}{\tau}\text{e} = \eta_T I_{\text{LED}},$$

and the rms value $i_{\text{rms,ph}}$ of this photocurrent:

$$i_{\text{rms,ph}} = \frac{\sigma_{N_{e,\text{photodiode}}}}{\tau}\text{e} = \sqrt{\eta_T \left(1 - \eta_T\right) N_{e,\text{LED}} \frac{\text{e}^2}{\tau^2}}$$

The bandwidth is $\delta f = 1/2\tau$, so the photocurrent noise is:

$$i_{\text{rms,ph}} = \sqrt{2\text{e}I_{\text{ph}} \left(1 - \eta_T\right) \delta f} \text{ (in A)}$$

instead of

$$i_{\text{rms,ph}} = \sqrt{2\text{e}I_{ph}\delta f}$$

for the shot noise. Thus, the noise power reduction is:

$$\frac{P_{\text{reduced}}}{P_{\text{photon}}} = 1 - \eta_T$$

In dB:

$$P_{\text{reduction,dB}} = P_{\text{reduced,dBm}} - P_{\text{photon,dBm}} = 10 \log \left(1 - \eta_T\right)$$

7 Short guidelines for the redaction of the report

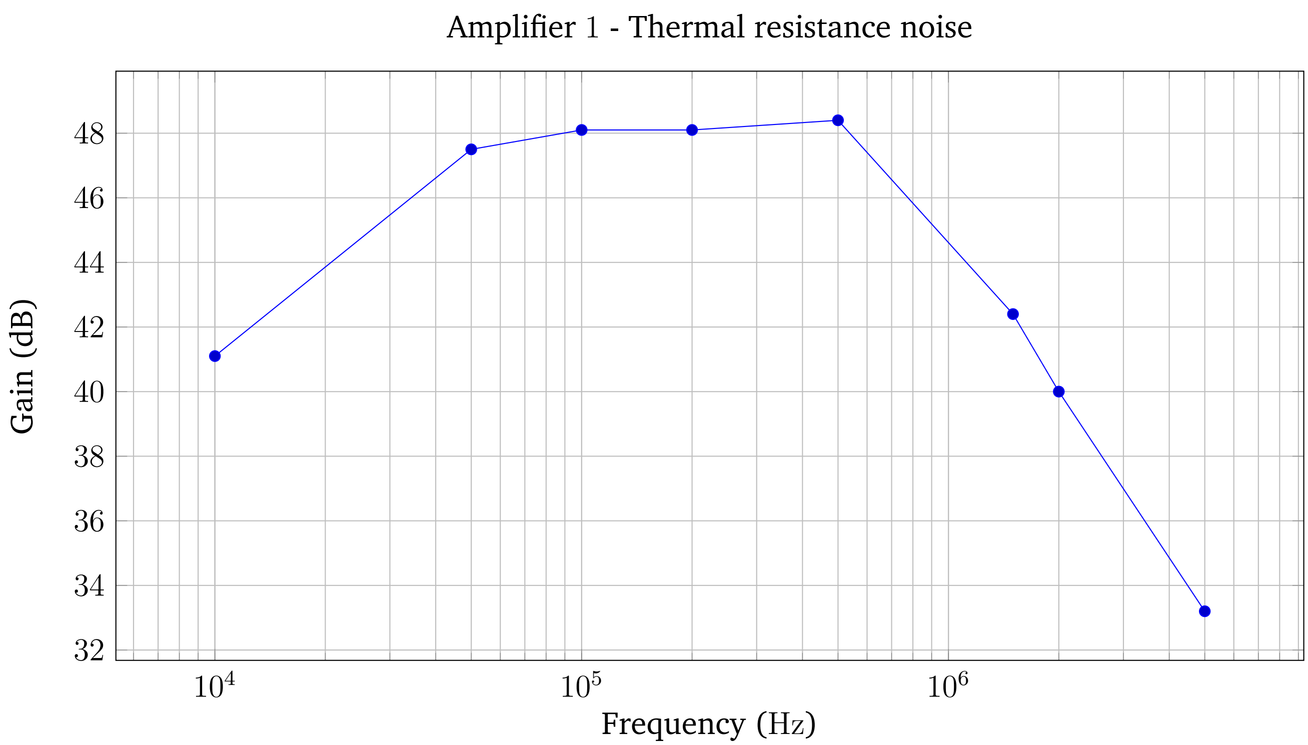
For the report, please do not answer all the questions of the text linearly and do not describe all your experimental procedures. Please explain for all three configurations what are the contributions to the noise, their nature and their rms levels. A particular attention will be paid to the graphs in Parts "Thermal resistance noise" (influence of the resistance) and "Photon noise". Thus, We expect you to establish a brief overview of the noise levels in the different setups under study. Redaction of the last part "Noise reduction" is optional, but will be strongly taken into consideration if satisfying.

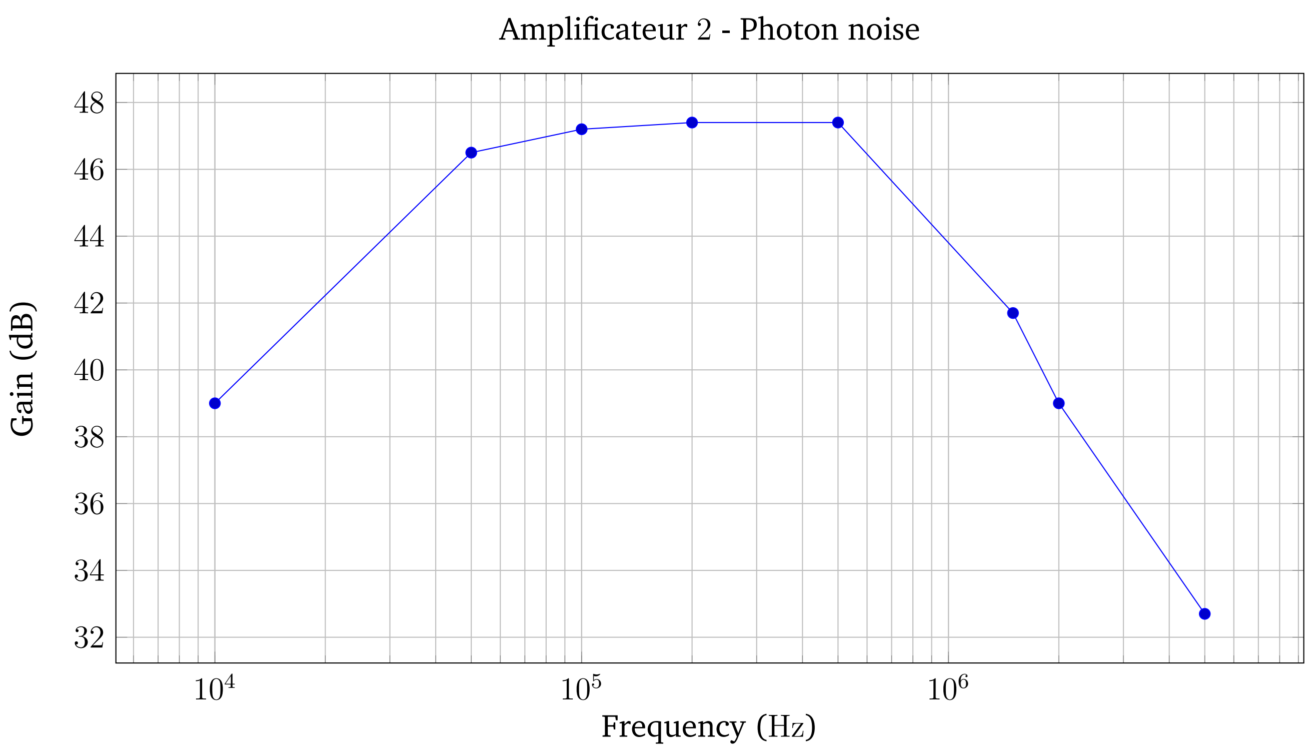
References on noise reduction

[1] Introduction à la réduction du bruit quantique. S. Reynaud
Ann. Phys. Fr. 15, 63 (1990).

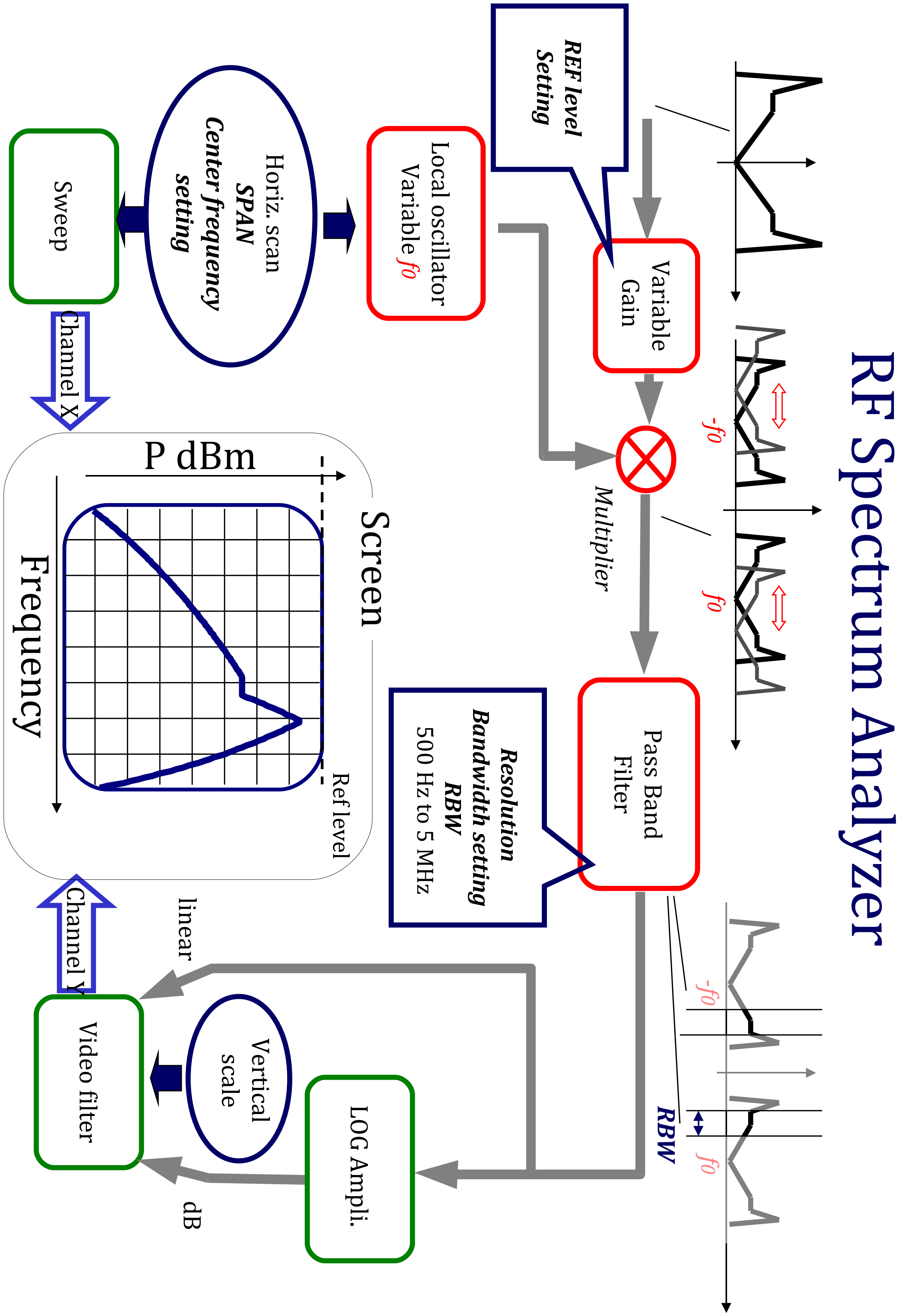
[2] Sub-Shot-Noise Manipulation of Light Using Semiconductor Emitters and Receivers. J.-F. Roch, J.-Ph. Poizat and P. Grangier
Physical Review Letters Vol 71, Number 13 (1993)

Appendix 1. Bode diagrams of the amplifiers





Appendix 2. The spectrum analyser



B 2

Infrared detector characteristic measurement

You should read carefully this text and prepare the questions P1-P12 before the lab.
Data analysis have to be done and checked during the lab session.

Contents

1 Objectives

At the end of the session lab, you will be able to:

- measure the performance of an infrared detector, which means being able to:
  - identify the relevant parameters (dark current, quantum efficiency, black-body response, noise , detectivity);
  - identify the specificities of the IR domain (black-body radiation, ambient background, dark current of the detector);
  - use a digital spectrum analyzer and understand the need for an antialiasing filter and an appropriate window;
  - understand the rational behind the use of a chopper;
  - be able to compute the etendue of the measurement setup;
  - evaluate the uncertainty of each measurement;

– propose a measurement procedure that can be used to verify if an IR detector is limited by the background photon noise (BLIP).

During this lab, we will therefore measure the characteristics of an IR detector cooled to $77\,\mathrm{K}$ by liquid nitrogen.
The detector is an ***InSb*** photodiode **(sensitive in the 3–5 microns spectral band)**, with model reference `P5968-100 Hamamatsu`. The diameter is $1\,\mathrm{mm}$ and the total angle of view is $60°$.
The full characteristics of the detector can be found online:
http://jp.hamamatsu.com

This lab will provide an opportunity to apply concepts learnt in the course of photometry and detectors noise, and to familiarize with conventional experimental techniques. Measurements are relatively simple and fast, but they must be understood and analyzed with care.

P1 For which applications, one may use infrared detectors? Give at least 3 examples. Describe the different families of infrared technologies and give their specificities.

2 Detector characteristics

2.1 Spectral response of a photonic detector

The spectral response $R(\lambda)$ of a photodiode detector is defined for a stationary monochromatic flux Φ_λ,

$$R(\lambda) = \frac{I_{\text{ph}}}{\Phi_\lambda} \text{ in } \mathrm{A}/\mathrm{W},$$

where I_{ph} is the mean current across the photodiode.

A photodiode is a quantum detector,*i.e.* a photon counter. So the current in the photodiode is easily related to the number of photons received per second, $n_{\text{ph},\lambda}$,

$$I_{\text{ph}} = \eta(\lambda) \cdot n_{\text{ph},\lambda} \cdot \mathrm{e},$$

where e is the electron charge and $\eta(\lambda)$ is the quantum efficiency (photon to electron conversion).

P2 Show that the spectral response of the detector is given by

$$R(\lambda) = \frac{I_{\text{ph}}}{\Phi_\lambda} = \frac{\lambda \cdot \eta(\lambda) \cdot \mathrm{e}}{\mathrm{h} \cdot \mathrm{c}} \text{ in } \mathrm{A\,W},$$

where h is the Planck constant $\mathrm{h} = 6.626 \times 10^{-34}\,\mathrm{J\,s}$.
We also define the **relative** spectral response of the detector:

$$S(\lambda) = \frac{R(\lambda)}{\max R(\lambda)} = \frac{R(\lambda)}{R(\lambda_{\text{peak}})}$$

P3 Explain why, if the quantum efficiency is constant, the spectral response $S(\lambda)$ for $\lambda < \lambda_{\text{peak}}$ is a linear function as represented on Figure 2.1.

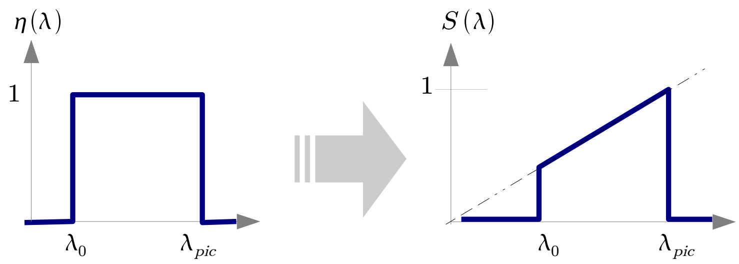


Figure 2.1: Spectral responsivity.

We will study an InSb detector whose cut off wavelength is: $\lambda_{\text{c}} = 5.5\,\mu\text{m}$.
The value corresponding to the peak of sensibility is $\lambda_{\text{peak}} = 5.3\,\mu\text{m}$.

P4 Calculate the maximal response $R\,(\lambda_{\text{c}})$ of a InSb detector at $\lambda_{\text{c}} = 5.3\,\mu\text{m}$ assuming the quantum efficiency is equal to 1.

The relative spectral response of the studied detector is obtained by comparison with a detector which spectral response is well known. For this purpose, one may use a pyroelectric detector as a reference. It is a thermal detector that has a constant spectral response. Some previous measurements are available on the computer.
See file `sensibilite_relative_insb.xls`.

2.2 Background infrared radiation

For IR detectors, the background photon flux detected is generally very large compared to the flux (signal) we want to measure (this explains why we need a chopper in front of our source in our setup). The black body emission of the whole scene at room temperature viewed by the detector is responsible for this large flux of background photons. This flux will be converted in a DC current, $I_{\text{ph,BG}}$. To determine this current, one needs to calculate the flux of background photons using Planck photonic black body law.

P5 Show that if the FOV (Field Of View) of the detector is 2α, the flux of photons received by the detector is:

$$n_{\text{ph,BG}} = \pi A_d \sin^2 \alpha \cdot L_{\text{ph,BG}} \text{ (in } \text{s}^{-1}\text{)},$$

where A_d is the area of the detector, and $L_{\text{ph,BG}}$ is the photonic total radiance between 2 and $5.5\,\mu\text{m}$,

$$L_{\text{ph,BG}} = \int_{2\,\mu\text{m}}^{5.5\,\mu\text{m}} \left[\frac{dL_{\text{ph}}}{d\lambda}\right]^{T_{\text{BG}}} d\lambda \text{ (in } \text{s}^{-1}\,\text{m}^{-2}\,\text{sr}^{-1}\text{)}.$$

The spectral photonic radiance is given by

$$\left[\frac{dL_{\text{ph}}}{d\lambda}\right]^T = \frac{2\text{c}}{\lambda^4}\frac{1}{\text{e}^{\frac{\text{hc}}{\lambda \text{k} T}} - 1} \tag{2.1}$$

where h is the Planck constant ($h = 6.626 \times 10^{-34}\,\text{J s}$) and k is the Boltzmann constant ($k = 1.38 \times 10^{-23}\,\text{J K}^{-1}$).

P6 Calculate $n_{\text{ph,BG}}$ for our detector (the diameter is $1\,\text{mm}$ and the half angle $\alpha = 30°$) if we assume that the quantum efficiency is 1 on the wavelength range $2 - 5.5\,\mu\text{m}$. Calculate the corresponding DC current $I_{\text{ph,BG}}$.

⇝ The total photonic radiance has to be calculated by integration of the spectral photonic radiance (2.1) on the wavelength range $2-5.5\,\mu\text{m}$. This integration can be done numerically with `Matlab` or `Excel` or using the webpage: http://www.spectralcalc.com/blackbody_calculator/blackbody.php

2.3 Background photon noise limit

The fluctuation of this flux of background photons is generally the main source of noise for IR detectors (these detectors are Background Limited Infrared Photodetectors or "BLIP") .

In this case, the noise current measured in a $1\,\text{Hz}$ equivalent Bandwidth is given by the Schottky formula :

$$i_{n,\text{BG}} = \sqrt{2\text{e}I_{\text{ph,BG}}} \text{ (in A}/\sqrt{\text{Hz}})$$

P7 Deduce $i_{n,\text{BG}}$ from the current $I_{\text{ph,BG}}$ calculated in question **P6**.

2.4 N.E.P.: Noise Equivalent Power

The Noise-Equivalent Power (NEP) is the radiant power that produces a signal-to-noise ratio of unity at the output of a given optical detector at a given modulation frequency, operating wavelength, and equivalent noise bandwidth.

$$\text{NEP}(\lambda) = \Delta\Phi_{\text{pp}}(\lambda) = \frac{i_{\text{noise, rms}}}{R(\lambda)} \text{ in W}$$

In other words the N.E.P. gives the smallest detectable variation of IR flux.

P8 Explain why the NEP is proportional to the square root of the effective bandwidth.

P9 For a BLIP detector, explain why the NEP is proportional to the square root of its surface?

Because the NEP is proportional to the square root of the detector surface and to the square root of the ENBW (Equivalent Noise Band Width), in order to compare different IR detectors we have to define the ratio:

$$\frac{\mathrm{NEP}\,(\lambda)}{\sqrt{A_d}\sqrt{\Delta f}}$$

where A_d is the detector area and Δf is the Equivalent Noise Band Width ENBW.

2.4.1 Spectral Detectivity

The detectivity, preferred by the manufacturers, is the inverse of the quantity defined above because the higher the detectivity, the better the detector is:

$$D^*(\lambda) = \frac{\sqrt{A_d}\sqrt{\Delta f}}{\mathrm{NEP}\,(\lambda)} = R\,(\lambda)\,\frac{\sqrt{A_d}\sqrt{\Delta f}}{i_{\text{noise, rms}}} = R\,(\lambda)\,\frac{\sqrt{A_d}}{i_{\text{noise, rms.@}1Hz}}$$

where $i_{\text{noise, rms.@}1Hz}$ is expressed in $A/\sqrt{\mathrm{Hz}}$, $D^*(\lambda)$ in $\mathrm{cm}\sqrt{\mathrm{Hz}}/\,\mathrm{W}$, as the detector area is expressed in cm^2.

The maximal value is obtained for λ_{peak} and is called peak detectivity **($\mathbf{D}^*_{\textbf{peak}}$)**.

P10 What is the value of $\mathbf{D}^*_{\textbf{peak}}$ according to the datasheet ?

2.5 Black body Detectivity

A direct measurement of the spectral detectivity versus the wavelength is difficult. So we will first measure the Black Body Detectivity (the detector is illuminated by a black body at $500\,\mathrm{K}$). Then we will measure the relative spectral response of the detector $S(\lambda)$.

The Black Body Detectivity $D^*_{\text{BB}}(T_{\text{BB}}, f, \Delta f)$ is:

$$\begin{aligned} D^*_{\text{BB}}\,(T_{BB}, f, \Delta f) &= R_{\text{BB}}\,\frac{\sqrt{A_d}\sqrt{\Delta f}}{i_{\text{noise, rms.}}\,(f)} \\ &= \frac{I_{\text{ph}}}{\Phi_{\text{BB},T_{\text{BB}}}}\,\frac{\sqrt{A_d}}{i_{\text{noise, rms.@1 Hz}}\,(f)} \end{aligned}$$

in $\mathrm{cm}\sqrt{\mathrm{Hz}}/\,\mathrm{W}$, where T_{BB} is the black body temperature, f the modulation frequency and Δf the ENBW.

P11 For which values of $T_{\textbf{CN}}, f, \Delta f$ is the black body detectivity given in the datasheet?

Remark From the measurements of $D^*_{\textbf{BB}}(T_{\textbf{BB}}, f, \Delta f)$ **and** $S(\lambda)$ we will deduce $D^*(\lambda)$ for this detector (see paragraph 4).

3 Measurements

The circuit diagram is given in Figure 2.2.

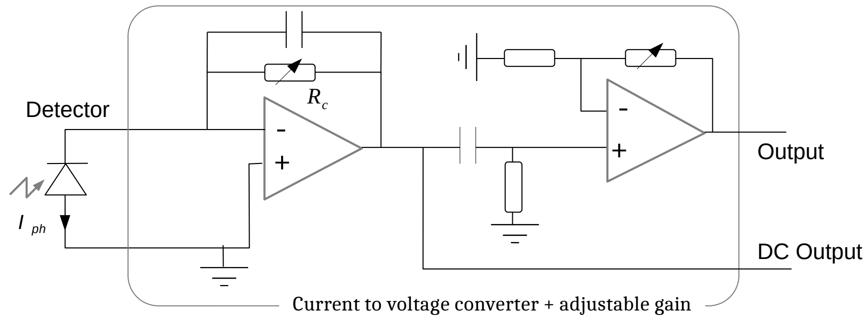


Figure 2.2: Circuit diagram.

P12 What is the name of the first stage of the detection circuit? What is the link between V_0 and I_{ph}? What is the bias voltage? What is the function of the second amplier? How about the RC filter between the two amplifiers?

3.1 Measurement of the current due to the background infrared radiation

⇝ Connect the detector to the amplifier box `Ampli détecteurs infrarouges` and the voltmeter to the `DC output`. Connect the output to the oscilloscope.

⇝ Pour slowly and carefully liquid nitrogen into the cryostat and wait for the signal apparition.

Q1 Measure the DC voltage. Deduce the value of $I_{\text{ph,BG}}$ and, compare it with the value determined at question **P6**.

3.2 Measurement of the detector noise

⇝ Connect the output of the amplifier box to the filter box texttttFiltre anti-repliement..

3.2.1 Noise measurement with an oscillloscope

⇝ Display the signal on the `RIGOL` oscilloscope. Choose properly the value of R_c and of the different gains in order to obtain a correct signal amplitude without any saturation.

Q2 Where does this noise come from? Assuming this noise is Gaussian, measure $V_{\text{noise,rms}}$ with the oscilloscope (you can use the theoretical framework provided by the subject of Labwork 9, and we remind you that $V_{\text{noise,rms}} = V_{\text{pp}}/6$ for a Gaussian noise).

Q3 The bandwidth of the anti-aliasing filter is about $2\,\mathrm{kHz}$. Assuming the noise is a white noise on this bandwidth, calculate $v_{\text{noise,rms@}1Hz}$ in a $1\,\mathrm{Hz}$ analysis bandwidth (rms noise voltage in $\mathrm{V}/\sqrt{\mathrm{Hz}}$). Deduce the current noise, $i_{\text{noise, rms.@}1Hz}$, in the photodiode for an equivalent bandwidth of $1\,\mathrm{Hz}$ (current noise normalized in $\mathrm{A}/\sqrt{\mathrm{Hz}}$). Compare to the value obtained in preparation (**P7**).

3.2.2 Accurate noise measurement with a FFT spectrum analyzer

⇝ Connect the signal on the 1$^{\text{st}}$ input channel of the `LeCroy` analyzer.

⇝ Upload the setup file named `TPDetIR HistBruit`. To do so, go to the menu `File>Recall Setup`.

⇝ Click on the `C1` yellow frame, located just below the plot area. Check that the coupling parameter is set to `DC1M`Ω or `AC1M`Ω if the additional high-pass filter has not been inserted into the setup. Change the parameter value if needed.

Q4 Can we consider that the noise measured by the analyzer is Gaussian? Explain why this approximation is physically relevant.

⇝ Now, upload the setup file named `TPDetIR TFBruit` in the menu `File>Recall Setup`. Check that the coupling parameter is still set to the correct value.

Q5 Is the measured noise a white noise? Was it expected?

Q6 Explain the role of the anti-aliasing filter. Where do you see its influence? Why is it necessary for this measurement? How should we choose the sampling frequency?

The background photon noise (detector noise) and the amplification noise are both responsible for the measured noise. These noise sources are statistically independent so:

$$v_{\text{total,rms}} = \sqrt{v^2_{\text{noise,rms}} + v^2_{\text{ampli,rms}}}$$

⇝ Go to the `Cursors` menu and select `Horizontal Abs`. Display the cursor settings in `Cursors>Cursor Setup` and select `Hz` as the `X - axis` parameter. The x-coordinate (frequencies) of the cursor is displayed on the right of the screen, its y-coordinate is displayed in the red and blue frames intitled `F1` and `F2` respectively. We remind you that $P_{\text{dBm}} = 10\log\left(\frac{P}{1\text{mW}}\right)$ where $P = V^2/1\mathrm{M}\Omega$.

Q7 Measure the noise voltage at the ouput for $500\,\mathrm{Hz}$. Then, for the same frequency, measure the noise voltage at the output when the detector is disconnected. Deduce the detector noise voltage $v_{\text{noise,rms}}$ and the current noise of the detector $i_{\text{noise,rms}}$.

Q8 Note the value of the equivalent noise bandwidth Δf displayed in the FFT panel that appears when you click on de red F2 frame. Deduce the noise current of the detector in 1Hz bandwidth $i_{\text{noise,rms@}1Hz}$. Compare to the value obtained in preparation (**P 7**). Is the detector BLIP?

3.3 Measurement of the black body response of the IR detector

To measure the black body response of the IR detector,

$$R_{\text{BB}} = \frac{\Delta I_{\text{ph}}}{\Delta \Phi_{\text{BB}}} \text{ in } \text{A} / \text{W}$$

we will have to:

- determine precisely the flux variation received by the detector,
- measure carefully the photocurrent induced by this flux variation.

3.3.1 Set-up

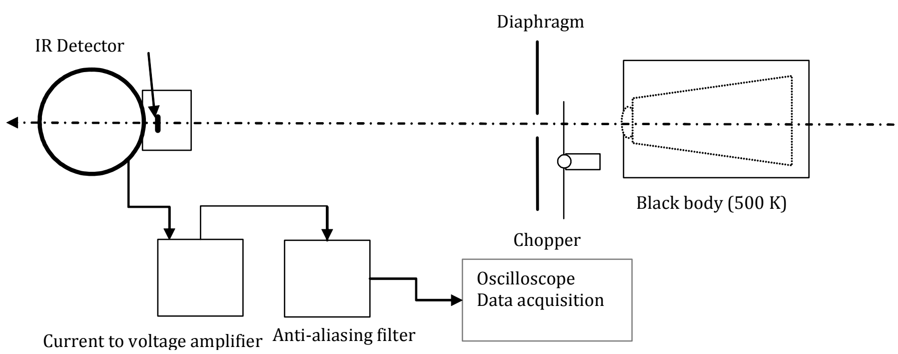


Figure 2.3: Set-up

When the chopper is turning, the detector sees through the diaphragm alternately a black blade at room temperature or the black body at $500\,\text{K}$.

Do not change the temperature settings of the black body!

3.3.2 First measurement using an oscilloscope

⇝ Set the modulator frequency to $500\,\text{Hz}$.

⇝ Place the detector precisely at 1 meter from the diaphragm (Detector is at $(9 \pm 1)mm$ behind the window).

⇝ Align carefully the Black Body, the diaphragm (we will choose a diameter $\phi = 5$ mm) and the detector.

⇝ Optimize the signal by improving your alignment.

Q9 Measure the peak to peak voltage without anti-aliasing filter.

The flux variation $\Delta\Phi(t)$ is periodic and can thus be decomposed as a Fourier series. One can then calculate the RMS value of its fundamental component $\Delta\Phi_{\text{rms}}$. One can show that RMS value is related to the peak to valley of the flux variation Φ_{pp} by the Modulation Factor (M.F.):

$$\text{MF} = \frac{\Delta\Phi_{\text{rms}}}{\Phi_{\text{pp}}} = \frac{\Delta\Phi_{\text{rms}}}{\Phi_{\text{max}} - \Phi_{\text{min}}} \tag{2.2}$$

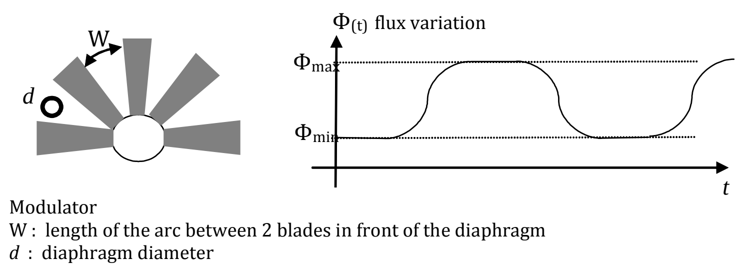


Figure 2.4: Chopper

For a square signal (case $d << W$):

$$\text{MF} = \frac{\sqrt{2}}{\pi} = 0.45$$

Q10 Show that the modulation factor for a square signal is:

$$\text{MF} = \frac{\Delta V_{\text{rms, 500 Hz}}}{V_{\text{peak to peak}}} = \frac{\sqrt{2}}{\pi} = 0.45$$

Deduce a value of $\Delta V_{\text{rms,500 Hz}}$.

Q11 Deduce a value of $\Delta I_{\text{BB, rms,500 Hz}}$.

3.3.3 Measurement of the signal obtained by the FFT method

⇝ Add the anti-aliasing filter (low-pass filter, cut-off frequency of $2\,\text{kHz}$) and connect the output signal to the `LeCroy` analyzer.

⇝ Go to the menu `File>Recall Setup` and upload the file `TPDetIR TF Signal`. The `P2` measurement channel gives the amplitude of the highest peak, the one at 500Hz.

Q12 Measure the RMS voltage after the filter at 500Hz.

⇝ Vary slightly the chopping frequency with an amplitude of $\pm 20\text{Hz}$.

Q13 Note the effective value of the highest peak measured by the analyzer during this variation. Explain the origin of these fluctuations. What is the influence of the acquisition window, the sampling frequency, F_e, and the influence of the number of acquired points N_e? Explain why the "flat top" window is theoretically well fitted for this kind of measurement (you can use the appendix for your explanations).

⇝ Set back the frequency to 500Hz. In the `FFT` panel of `F2` channel, select the *Flat Top* window.

Q14 Measure the amplitude of the 500Hz peak. Knowing the gain of the amplifier and of the filter (in V/A), measure the current, $\Delta I_{\text{BB, rms,500 Hz}}$ through the photodiode. Evaluate the accuracy of this measurement.

⇝ Check your result with the lab instructor.

3.3.4 Determination of the flux variation received by the IR detector

Calculation of the peak to peak flux variation

Q15 Measure the diaphragm - detector distance and calculate the etendue between the detector and the diaphragm (the InSb detector diameter is $1\,\text{mm}$).

The black body radiance follows the Stefan law:

$$L = \frac{\sigma T^4}{\pi}$$

with $\sigma = 5,67.10^{-8}\ \text{W}/\text{m}^2.\text{K}^4$

Q16 Calculate the peak to peak flux variation received by the IR detector $\Delta\Phi_{\text{BB,pp}}$.

Calculation of the effective variation of the flux received by the detector

Q17 Using Eq. (2.2), calculate $\Delta\Phi_{\text{rms,500 Hz}}$ received by the detector.

3.3.5 Black body response of the detector

Q18 Calculate the black body response of the IR detector $R_{\text{BB}} = \frac{\Delta I_{\text{ph}}}{\Delta\Phi_{\text{BB}}}$

⇝ Check your result with the lab instructor.

3.3.6 Calculation of the black body detectivity

Q19 Deduce the black body detectivity $D^*_{\mathbf{BB}}(T_{\mathbf{BB}}, f, \Delta f)$. Evaluate the accuracy of your measurement.

The detector noise is normally mainly due to the photon noise of the ambiant photons. In this case, the noise of the detector depends on the field of view (FOV).

Q20 Explain why the noise of the detector depends on the FOV. How should $D^*_{\mathbf{BB}}(T_{\mathbf{BB}}, f, \Delta f)$ be corrected to be compared with a 2π steradian detector?

4 Analysis of the measurements

In this section, no measurement is required. However, you will need the file `sensibilite_relative_` which is saved on the computer of the room. Do not forget to make a copy of the file.

Spectral Response and spectral detectivity

With the measurements of the black body Response, R_{BB} and the relative spectral Response, the spectral response can be deduced:

$$\gamma = \frac{R\left(\lambda_{\text{peak}}\right)}{R_{\text{BB}}}$$

The photonic current is given by

$$\Delta I_{\text{ph}} = R_{\text{BB}} \Delta \Phi_{\text{BB}}$$

with :

$$\Delta \Phi_{\text{BB}} = \text{MF} \times \frac{\sigma}{\pi} \left(T_{\text{BB}}^4 - T_{\text{BG}}^4\right) U$$

where U is the etendue, MF is the modulation factor, BB refers to the blackbody temperature and BG to background temperature.

E1 Explain why the photonic current can also be calculated by integration of the black body radiance :

$$\begin{aligned} I_{\text{ph}} &= \text{MF} \times U \times \int_0^\infty R\left(\lambda\right) \left(\left[\frac{dL}{d\lambda}\right]_{\text{BB}}^{T_{\text{BB}}} - \left[\frac{dL}{d\lambda}\right]_{\text{BG}}^{T_{\text{BG}}} \right) d\lambda \\ &= \text{MF} \times U \times R\left(\lambda_{\text{peak}}\right) \int_0^\infty S\left(\lambda\right) \left(\left[\frac{dL}{d\lambda}\right]_{\text{BB}}^{T_{\text{BB}}} - \left[\frac{dL}{d\lambda}\right]_{\text{BG}}^{T_{\text{BG}}} \right) d\lambda \end{aligned}$$

where $\left[\frac{dL}{d\lambda}\right]_{\text{BB}}^{T_{\text{BB}}}$ and $\left[\frac{dL}{d\lambda}\right]_{\text{BG}}^{T_{\text{BG}}}$ are the spectral radiances of the black body at temperature at T_{BB} and T_{BG}, given by :

$$\left[\frac{dL}{d\lambda}\right]_{\text{BB}}^{T} = \frac{2\text{hc}^2}{\lambda^5}\frac{1}{\text{e}^{\frac{\text{hc}}{\lambda \text{k} T}} - 1}$$

where λ expressed in m, $\frac{dL}{d\lambda}$ in $\left(\text{W} \cdot \text{m}^{-2} \cdot \text{sr}^{-1}\right) / \text{m}$

E2 Deduce the ratio γ :

$$\gamma = \frac{\frac{\sigma}{\pi}\left(T_{\text{BB}}^4 - T_{\text{BG}}^4\right)}{\int_0^\infty S\left(\lambda\right)\left(\left[\frac{dL}{d\lambda}\right]_{\text{BB}}^{T_{\text{BB}}} - \left[\frac{dL}{d\lambda}\right]_{\text{BG}}^{T_{\text{BG}}}\right) d\lambda}$$

E3 Perform this calculation using Excel.

E4 Calculate $R(\lambda_{\text{peak}})$ and give the representation of the spectral Response $R(\lambda)$. Plot also the spectral quantum efficiency curve.

E5 Using γ, calculate $D^*_{\textbf{peak}} = D^*(\lambda_{\text{peak}})$ and plot the spectral detectivity curve $D^*(\lambda)$.

5 Writing down the report

In your report, you do not have to linearly describe your measurement protocols and your results. However, you should write a well structured document (between 2 and 6 pages maximum with an introduction, a conclusion, several parts, etc.) where you will summarize:

- the major concepts related to the technology you studied in the labwork,
- the key points and challenges of the characterization of an IR detector,
- your conclusions of the performance of the detector you studied during the labwork.

Your comments should be based on your measurements. You may also compare your observations on the infrared technology with what you know about sensors in the visible range.

Appendix 1 - Black body spectral radiance

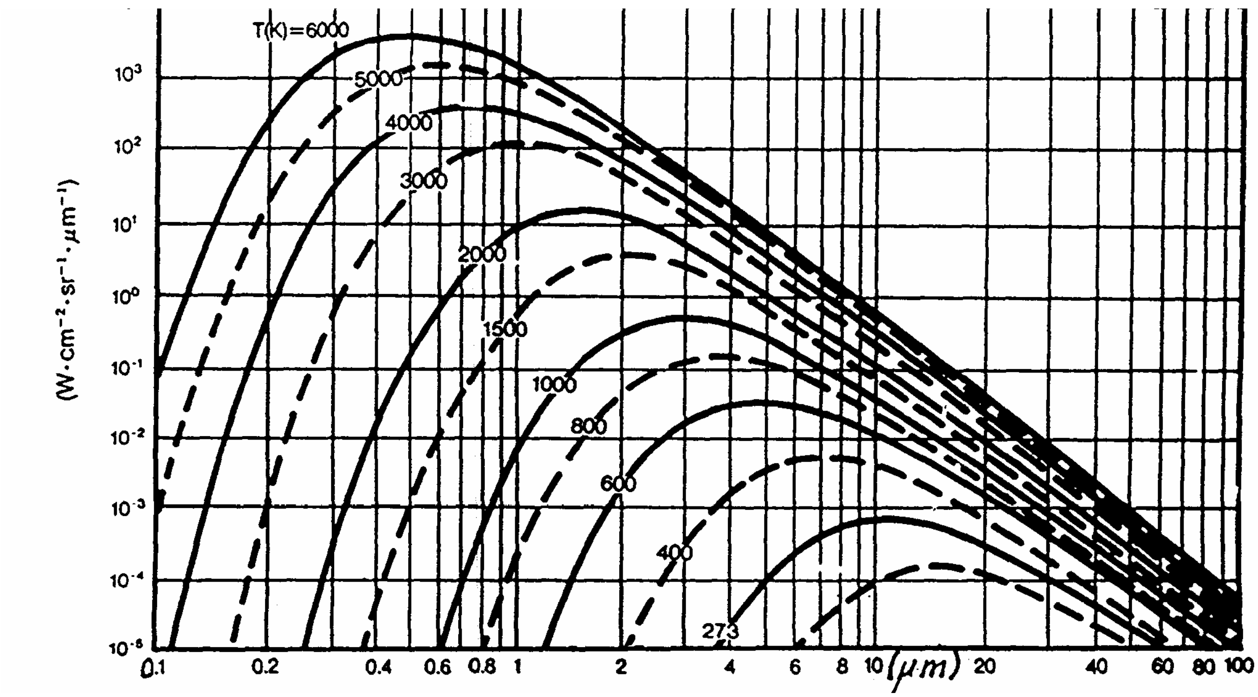


Figure 2.5: Black Body spectral radiance

Appendix 2 - Atmospheric transmittance

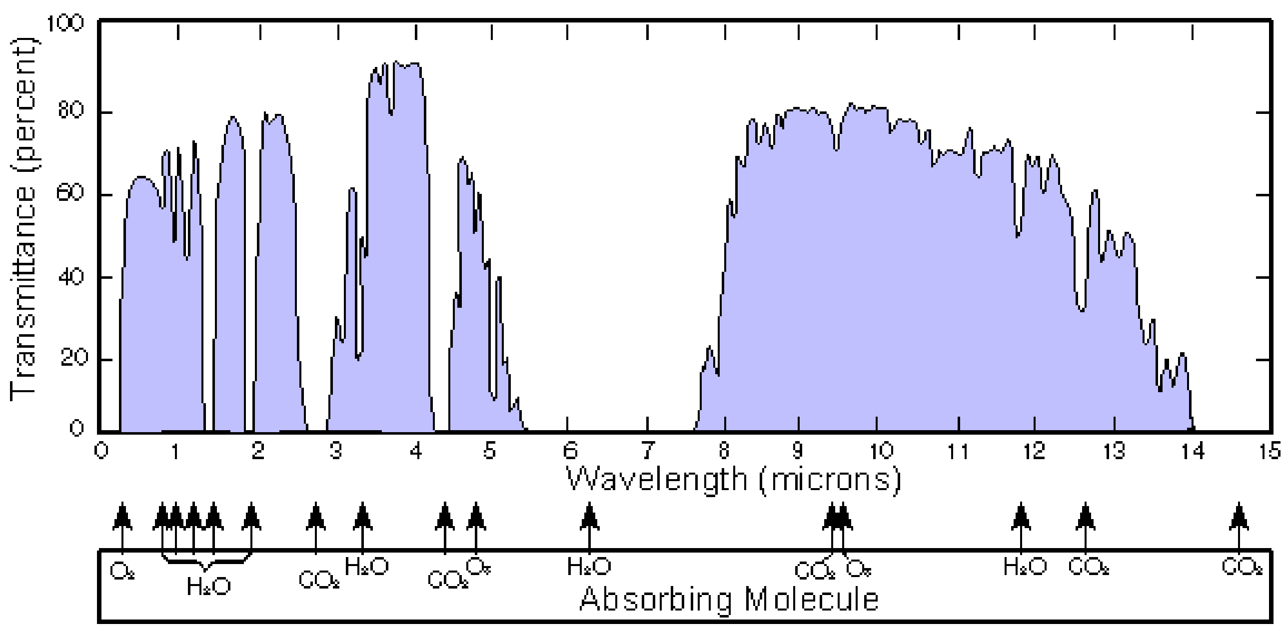


Figure 2.6: Atmospheric transmittance

Appendix 3 - Spectral detectivity

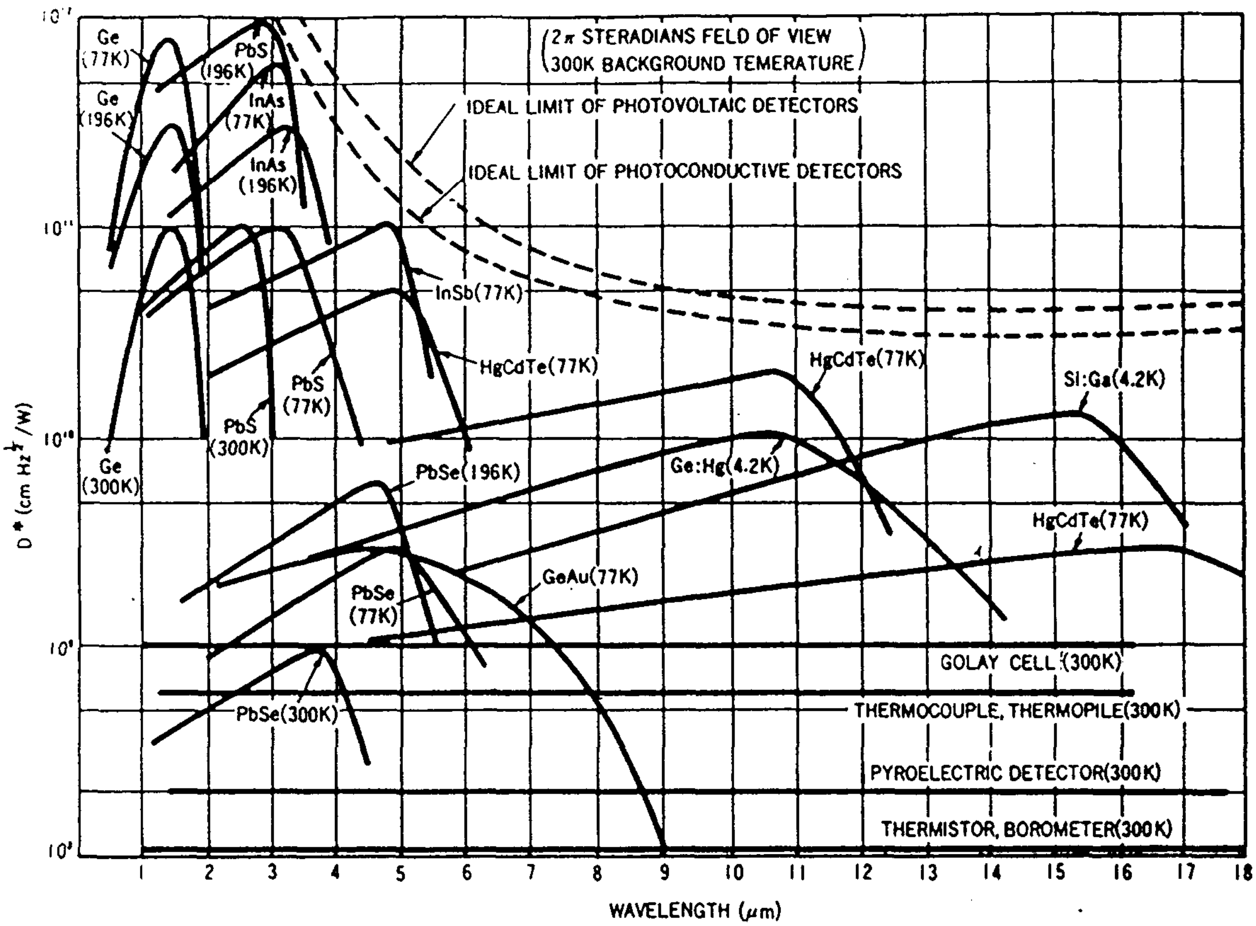


Figure 2.7: Spectral detectivities of IR detectors

B 3

CMOS sensor

Questions P1 to P4 must be prepared before the session.

Contents

1 Introduction

1.1 CMOS vs CCD

Today, most cameras are based on **CMOS (*Complementary Metal Oxide Semiconductor*)** sensors. They have gradually replaced **CCD (*Charge-Coupled Device*)** sensors, which were widely used in the past.

The main difference between CMOS and CCD sensors lies in the way the signal is read. In a CMOS sensor, each pixel has its own electronic circuit that converts the light signal (charge) into a voltage and amplifies it. This circuit is located directly next to the photosensitive area of the pixel.

Compared to CCD technology, CMOS technology offers several advantages:

- **Lower manufacturing cost**, because CMOS sensors are easier to produce,
- **Lower power consumption**,
- **Faster image readout**,
- **Independent control of each pixel**, which allows advanced image processing such as defining regions of interest (ROI), binning, filtering, and more.

However, CMOS sensors also have some drawbacks: their dynamic range is usually lower, and the noise level can be higher than with CCD sensors.

1.2 Lab Objectives and CMOS Sensor

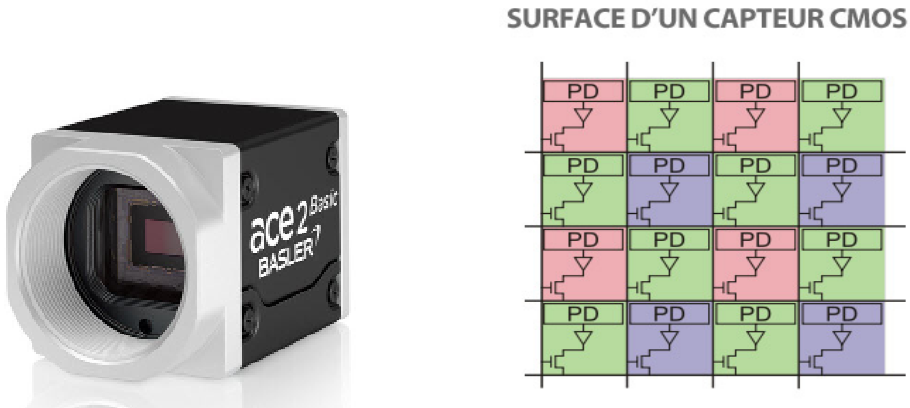


Figure 3.1: Basler ace2 CMOS camera – including the Sony IMX392 CMOS sensor – and schematic of a CMOS sensor

The purpose of this lab is to measure the characteristics of an industrial `Basler` camera equipped with a CMOS sensor manufactured by `SONY` (2.3 Mpix – $3.45\,\mu\text{m}$ square pixels), as shown in Figure 3.1.

We will focus in particular on the **sensor response and linearity**, the **readout noise**, the **dark signal**, and the **photon noise**. These characteristics will be compared to the manufacturer's specifications.

*Part of the technical documentation for the **Basler a2A1920-160umBAS** camera is provided in the appendix of the lab manual. The main parameters are summarized in the table below, the sensor temperature being equal to* $T_{internal} = 41\ ^{\circ}\text{C}$*:*

Resolution (pixels)	1920 x 1200	Bit Depth	12 bits
System Gain (K)	0.377 DN/e-	(1/K)	2.54 e-/DN
Signal-to-Noise Max	40.2 dB	Dark Current variance	0.027 e-/s
Quantum efficiency	62.22	Pixel size	3.45 x 3.45 μm^2
Dark Signal	1 DN/s		

DN = Digital Number -also called- ADU = Analog-Digital Units

2 Preparation Questions

Each **pixel** of this camera can be considered as a **photodiode** together with its **pre-amplification circuit**. The resulting voltage from each pixel is then converted into a digital value by a **12-bit analog-to-digital converter (ADC)**. This digital data is subsequently read, pixel by pixel, by the PC via a USB connection.

P1 Draw a functional diagram of the data acquisition chain, indicating the type of information that is transmitted from each block to the next.

The dynamic range of this sensor is given by the **maximum number of photoelectrons per pixel** (*Full Well* or *Saturation Capacity*). This value also determines the sensor's signal-to-noise ratio (SNR).

P2 According to the documentation, the maximum number of electrons per pixel is 10492 (*Saturation Capacity*). Since the signal is digitized over 12 bits, ideally, how many electrons correspond to one digital level? Compare the result with the datasheet.

Note: This conversion factor, i.e., digital level / number of electrons, is often called the **Gain** (K) in the documentation, expressed in ***ADU/e-*** (*Analog-Digital Units per electron*) or DN/e- (*Digital Number per electron*).

P3 Assuming that photon noise dominates over all other noise sources, the pixel signal-to-noise ratio is directly related to the *Full Well*. Calculate the signal-to-noise ratio in dB for the case where the signal is at its maximum, and check the value of 40.2 dB given by the manufacturer.

P4 Suppose that, for a given scene, the signal-to-noise ratio (SNR) of our camera is insufficient (that is, the signal is buried in the noise). Can the SNR be improved by changing the integration time? What limitations will we ultimately face?

3 Getting Started with the Camera and Software

3.1 Graphical Interface for Image Acquisition

⇝ Launch the control interface by double-clicking the **`start CMOS.bat`** icon on the desktop.

⇝ In the left-hand menu, click on `Caméra Basler`. After a few seconds, the camera image will appear in the central display area (see Figure 3.2).

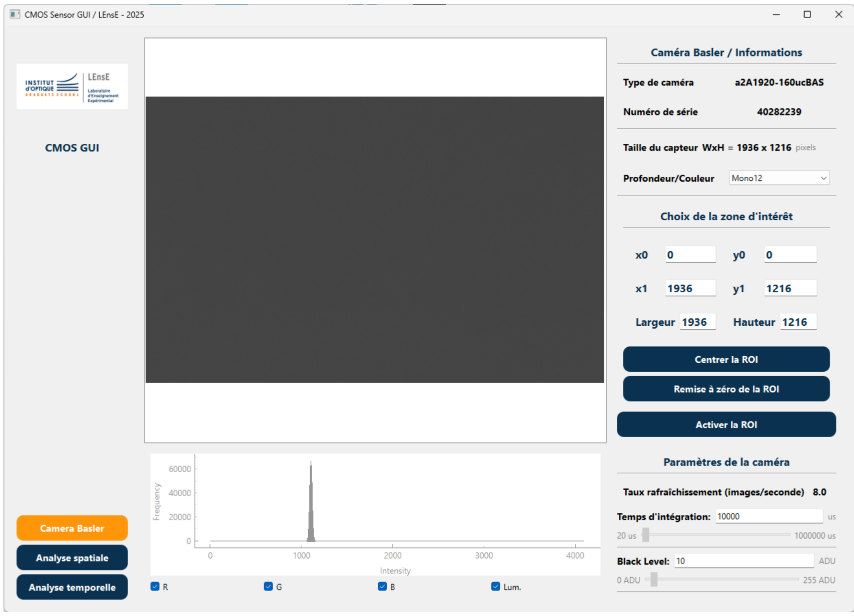


Figure 3.2: Camera control interface

If the camera is not recognized, check the USB connection and restart the application.

⇝ Once the camera is detected, set the `Black Level` (or *offset*) to 10.

⇝ If needed, select a **Region of Interest (ROI)** by clicking on two points in the camera image. Then click on `Activer la ROI`.

The Region of Interest (ROI) allows you to select a specific part of the image – the area of interest for processing – which also speeds up data transfer.

⇝ Adjust the `Temps d'Intégration` (or exposure time).

Q1 What does the histogram of an image represent? What happens to the histogram shown below the camera image when you change the integration time?

3.2 Comparison With and Without a Camera Lens

In typical imaging applications, it is essential to place a lens in front of the camera sensor.

⇝ A lens is available on the table: attach it to the camera. Adjust the integration time if necessary to obtain a non-saturated image of the scene.

Q2 What differences can be observed in the image captured by the camera with and without the lens? Why?

By default, this camera has a **bit depth** of 12 bits (*Mono12*). The option `Profondeur /Couleur` allows you to "reduce" this performance.

Q3 What is the maximum gray level represented in the histogram?

⇝ Change the option to *Mono8*.

Q4 What do you observe in the image and in the histogram? Using fewer bits allows faster data processing. But what is the disadvantage?

Q5 For the rest of the lab, we will use the "bare" camera sensor, without a lens: why?

⇝ Remove the lens for the rest of the lab.

⇝ Restore the bit depth to 12 bits (*Mono12*).

3.3 Sensor Uniformity

⇝ Click on the `Analyse Spatiale` button in the left-hand menu to display the histogram of the image.

⇝ Click on a region of the image. A cross will appear on the image (horizontal line in blue and vertical line in orange), and the corresponding data will be displayed in the graph to the right of the image.

You can click anywhere else on the image at any time to move the data sampling location.

Q6 What do these graphs represent? Comment on the shape of the curves obtained.

4 Readout Noise Measurement

Readout noise is an **electronic noise** that appears during the conversion of the number of photoelectrons into a voltage. This voltage is then converted into a 12-bit digital signal. To measure the readout noise, the sensor must receive no light, and the integration time should be set to zero (so that there is no dark signal).

⇝ Place the camera cover in front of the sensor array.

⇝ Click on the `Analyse Spatiale` button in the left-hand menu to display the image histogram.

It is possible to enlarge the useful part of the histogram by checking the `Zoom de l'histogramme` box. You can also save the histograms (full or zoomed) as PNG files by clicking on:

- `Sauvegarder l'histogramme` or
- `Sauvegarder le zoom de l'histogramme`.

⇝ Set the `Temps d'Intégration` to its minimum value.

Q7 Record the mean value and the standard deviation displayed under the histogram. What do these two values represent? (*Black Level* set to 10)

⇝ Adjusting the `Black Level` changes the previously measured mean level, which is commonly called the *bias* (as it corresponds to an offset).

Q8 Observe the histogram for a *Black Level* set to 0, 10, 128, and 255. Record the mean level in the image and the corresponding standard deviation for each case. Explain the effect of adjusting the *Offset*.

The **readout noise** is the fluctuation of the signal around this mean value.

⇝ Measure the readout noise of the sensor from the histogram.

NOTE: For the rest of the lab, always set the **Black Level** to **10**.

5 Study of the Dark Signal

We now focus on the images obtained on the sensor in complete absence of light, while increasing the integration time. These images are often called *Dark* images.

The sensor receives no light flux. We will vary the **integration time** (T_i).

⇝ Measure the mean gray level values and the standard deviations from the histogram, for integration times ranging from 0 to 300 milliseconds in steps of 30 ms.

⇝ Plot the dark signal as a function of the integration time, making sure to subtract the *offset* level.

Q9 Compare the measured dark signal with the value (*Dark Signal*) provided by the manufacturer. Why is the value measured in the lab different from the one provided by the manufacturer? How could this value be reduced?

⇝ Observe the "starry sky" appearance of the image for long integration times by enabling the AJUSTEMENT DU CONTRASTE option (in ANALYSE SPATIALE mode). Some pixels (often called *Hot Pixels*) show a much higher signal.

This is not temporal noise, but rather a **spatial non-uniformity of the dark signal**. Note also that the histogram is far from Gaussian.

⇝ Plot the dark noise as a function of the integration time, making sure to subtract the *offset* noise level.

Q10 Give the slope of the curve. How could this value be reduced?”

6 Study of Sensor Linearity and Photon Noise

We will now study the response of the CMOS sensor when it is uniformly illuminated using an integrating sphere. Images obtained under such uniform illumination are often called "*flat*" images.

⇝ Set the sensor integration time to 120 ms.

⇝ Illuminate the integrating sphere to achieve a mean gray level of approximately 2000.

6.1 Spatial Analysis – Linearity

To measure the **sensor linearity**, simply measure the mean signal as a function of integration time (remember to subtract the mean dark signal).

⇝ In CAMERA BASLER mode, select a region of interest (ROI) of approximately 200 x 200 pixels, centered. and click on ACTIVER LA ROI.

⇝ Switch back to ANALYSE SPATIALE mode.

⇝ Vary the exposure time from 0 to 300 ms in steps of 30 ms, and record the mean gray levels as well as the standard deviation.

Q11 What can you say about the last point? Identify the *Full Well* (or *Saturation Capacity*) from the plotted curve.

⇝ Plot the mean signal as a function of integration time.

Q12 Is the sensor linear?

Q13 Plot the signal-to-noise ratio (SNR) as a function of the mean signal. Comment.

6.2 Temporal Analysis – Photon Noise

To measure the photon noise, we need to track the fluctuations of a single pixel's signal over time (from one image to another), for different illumination levels on the pixel. It is important to account for the influence of readout noise in this analysis.

⇝ Set the sensor integration time to 120 ms.

⇝ Illuminate the integrating sphere to achieve a gray level of approximately 2000.

⇝ Select the ANALYSE TEMPORELLE menu. Choose the number of points (NOMBRE DE POINTS) and click LANCER UNE ACQUISITION.

⇝ Display the signal profile over time for 4 randomly selected pixels in the image at this gray level.

⇝ Observe that the noise indeed appears random over time, and that the histogram seems to follow a Gaussian distribution.

Note: To obtain meaningful histograms, a large number of points should be recorded (around 500 to 1000).

⇝ Repeat this measurement of a single pixel profile for different mean illumination levels (500, 1000, 1500, 2500, 3000), by adjusting the illumination of the integrating sphere.

⇝ Plot the signal variance as a function of the mean signal.

Q14 Does the measured noise behave as expected for **photon noise**? Explain.

If this is indeed photon noise, i.e., Poisson noise, the fluctuation of the number of photoelectrons per pixel is given by its variance:

$$\sigma_{N_e}^2 = \langle N_e \rangle$$

The number of photoelectrons is converted into a digital signal, $S_{12\text{bits}}$:

$$S_{12\text{bits}} = N_e \times K$$

where K is the conversion factor (gain) in digital number per electron (ADU/e- or DN/e-).
The mean value of the digital signal is:

$$\langle S_{12\text{bits}} \rangle = \langle N_e \rangle \times K$$

and the variance of the digital signal is:

$$\sigma_{S_{12\text{bits}}}^2 = \sigma_{N_e}^2 \times K^2$$

It is therefore possible to deduce from the previous measurements the conversion factor (gain) in electrons per digital level (e-/ADU):

$$K = \frac{\sigma_{S_{12\text{bits}}}^2}{\langle S_{12\text{bits}} \rangle}$$

Q15 Calculate the value of the conversion factor and compare it with the value obtained in question **P2**.

Q16 Explain why there is a difference between the noise obtained by studying the temporal fluctuations of a single pixel and the noise obtained by analyzing the histogram of a 200 x 200 pixel region at the center of the image.

7 Measurement of the Sensor Spectral Response

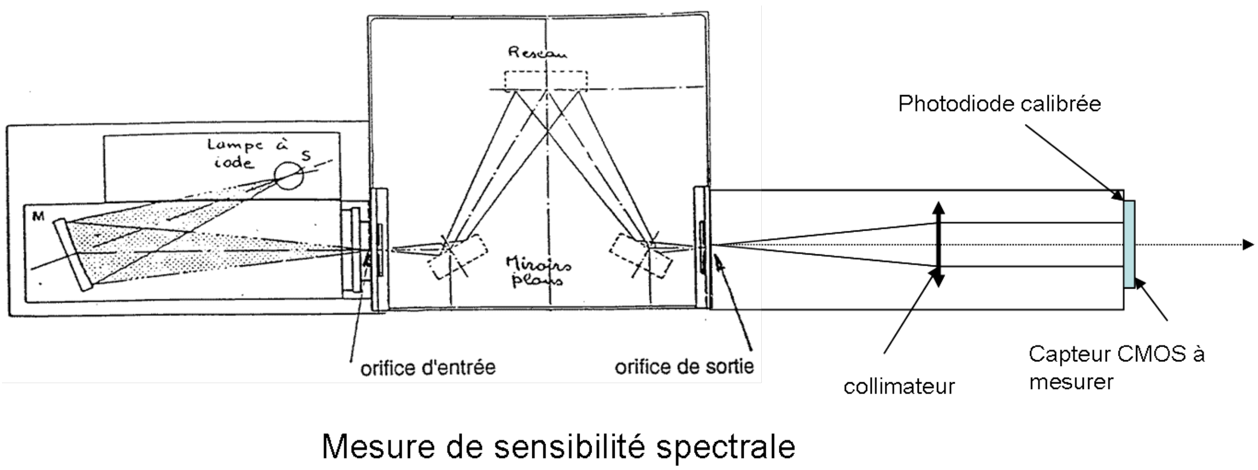


Figure 3.3: Schematic of the spectral sensitivity measurement setup using a monochromator

The **monochromator** allows selection of the wavelength of the light flux sent to the sensor. The entrance and exit slits are 2 mm wide, giving a spectral width of approximately $30\,\mathrm{nm}$. At the monochromator output, a collimator illuminates the sensor under test at nearly normal incidence.

A `Pin 10-D` photodiode with a $1\,\mathrm{cm}^2$ area is used to measure the irradiance received by the CMOS sensor. The sensitivity of this photodiode is provided below.

⇝ Power the monochromator with a voltage of approximately $20\,\mathrm{V}$.

⇝ Select a region of interest of 200 x 200 pixels at the center of the sensor.

⇝ Set the integration time to 30 ms.

⇝ Measure the irradiance (in $\mathrm{W/cm^2}$) with the photodiode for the following wavelengths (λ): $500, 550, 600, 650, 700, 750, 800, 850, 900\ \mathrm{nm}$.

⇝ Replace the photodiode with the CMOS sensor. Measure the mean gray level at the center of the image for these wavelengths. Choose an appropriate exposure time.

⇝ From these measurements, determine the spectral response of the sensor, expressed as gray level versus energy received per cm^2, in units of $\left(\frac{\mathrm{ADU}}{\mathrm{nJ/cm^2}}\right)$.

Q17 Plot this spectral response curve.

Q18 Determine the quantum efficiencies for these wavelengths and plot the curve of quantum efficiency versus wavelength. Compare it with the curve provided in the Datasheet.

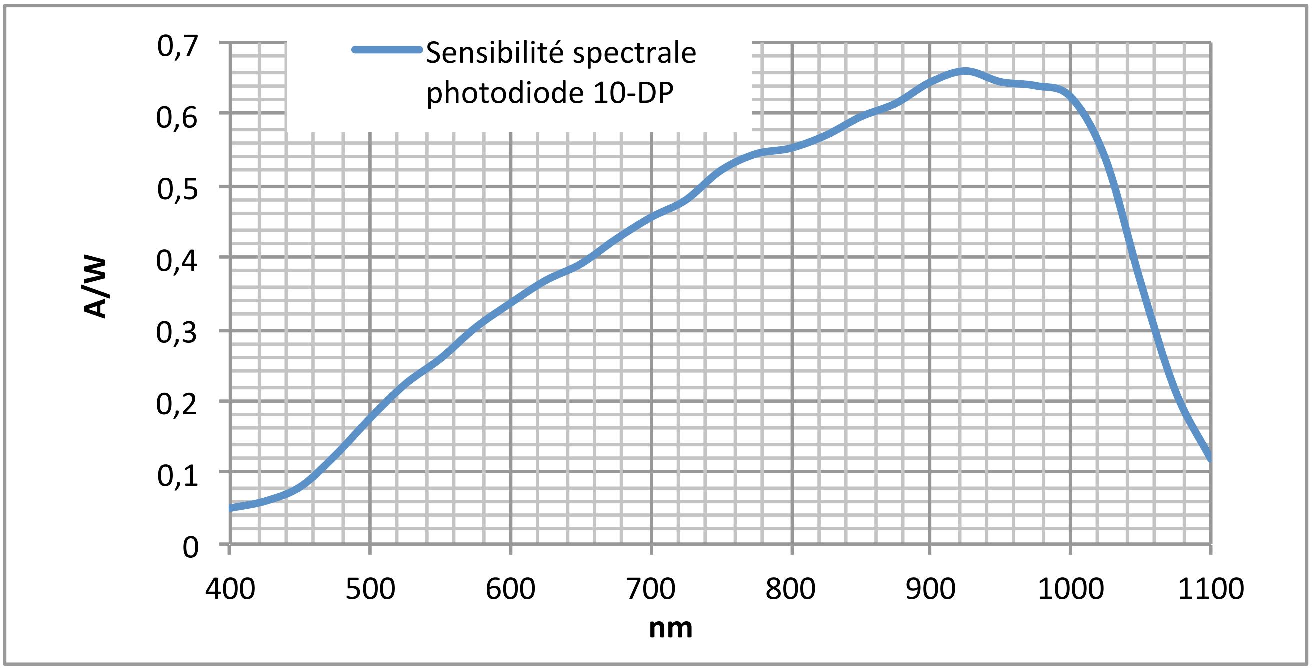


Figure 3.4: Spectral sensitivity curve of the calibration photodiode

Summary

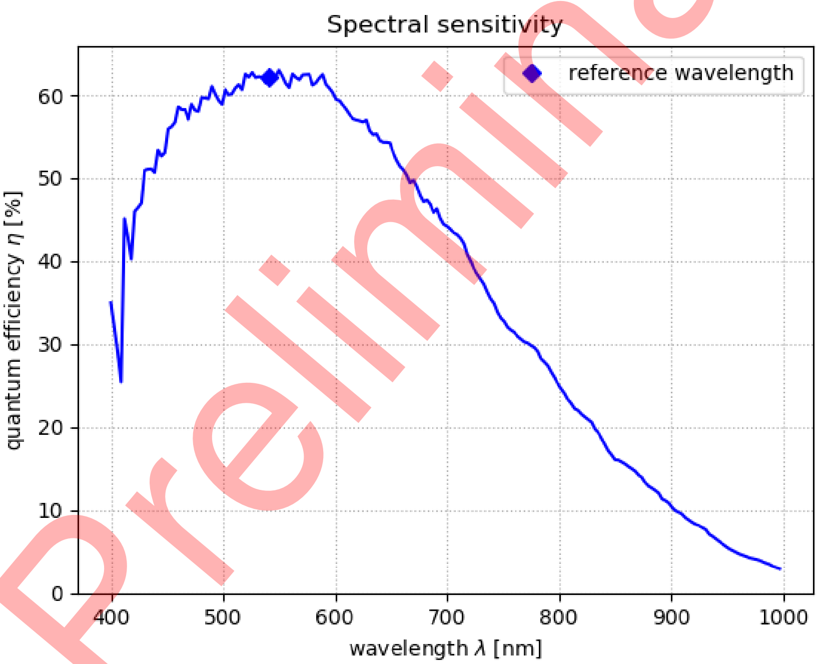
In a summary (maximum 2 pages, excluding figures), explain to an industrial user who wants to calibrate a newly acquired CMOS sensor which steps to follow and what types of curves they should obtain. You may refer to your experimental results.

a2A1920-160umBAS EMVA 1288 Datasheet

This datasheet describes the specification according to the standard 1288 Standard for Characterization and Presentation of Specification Data for Image Sensors and Cameras of European Machine Vision Association (EMVA) (See www.standard1288.org).

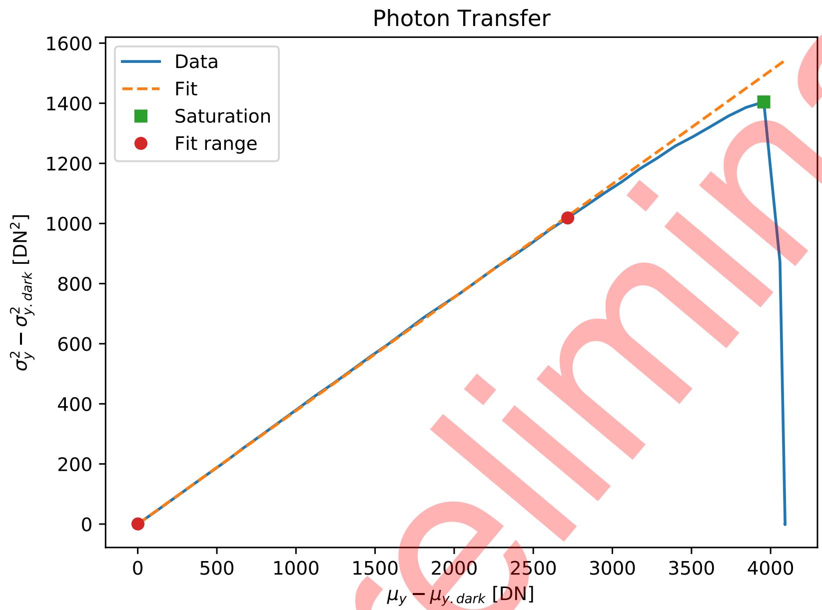
Sensor Specification

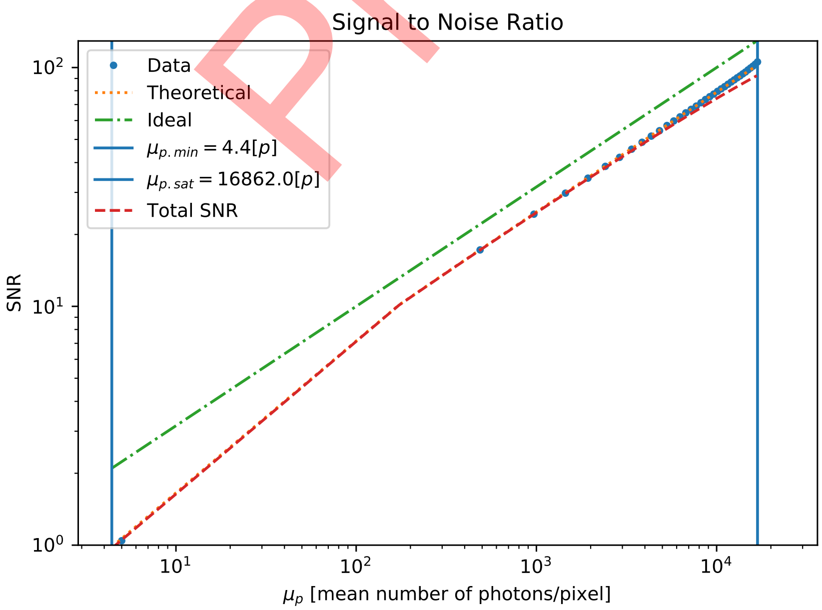
Vendor	Basler	Shutter mode	None
Model	a2A1920-160umBAS	Light source	Integrating sphere
Sensor	IMX392	EMVA1288 standard version	3.1
Resolution	1920 px x 1200 px		
Pixel size	3.45 x 3.45 μm^2		



Operating Point

Camera setting	
Pixel format	Mono12
Gain	0.0
Black level	4.0
Bit depth	12 bit
Grab mode	Continuous
Non overlapped	True
Frame rate	10 fps
Operating point parameters	
Exposure control	By camera exposure time
Exposure minimum	20 μs
Exposure maximum	90661 μs
Exposure time steps	50
Spatial exposure time	33401 μs
Spatial image count	150
Housing temperature	32.63 °C
Internal temperature	40.78 °C
Ambient temperature	20.75 °C
Illumination	LED
Illumination wavelength	541 nm
Spectral width (FWHM)	38 nm
Irradiance	0.8 μW/cm^2





Performance

Quantum efficiency

η	62.22 %

System gain

K	0.377 DN/e^-
1/K	2.652 e^-/DN

Temporal dark noise

σ_d	2.542 e^-
$\sigma_{y.dark}$	0.845 DN

Signal-to-noise ratio

SNR_{max}	102
	40.21 dB
	6.7 bit
SNR_{max}^{-1}	0.976 %

Absolute sensitivity threshold

$\mu_{p.min}$	4.407 p
$\mu_{e.min}$	2.742 e^-

Saturation capacity

$\mu_{p.sat}$	16862 p
$\mu_{e.sat}$	10492 e^-

Dynamic range

DR	3826
	71.7 dB
	11.9 bit

Spatial nonuniformities

$DSNU_{1288}$	0.5 e^-
	0.2 DN
$PRNU_{1288}$	0.5 %

Linearity error

LE_{min}	-0.348 %
LE_{max}	0.576 %

Dark current

$\mu_{I.mean}$	nan e^-/s
$\mu_{I.var}$	0.027 e^-/s

B 4

Thermal camera

Do not forget to prepare the preliminary questions before the lab. Some of them can be asked during the oral examination.

Contents

This lab will allow you to take in hand two infrared cameras of microbolometer technology (figure 4.1), to characterize their performances then to approach two applications of infrared imaging.

The first part of the lab is devoted to the discovery of infrared and the highlighting of certain properties of materials in the infrared (emissivity, transparency/opacity...). Then, you will evaluate the performance of both cameras by measuring their NETD (noise equivalent temperature difference). You will then focus on two applications of infrared imaging: absolute temperature measurement (infrared thermography) and non-destructive testing.

The lab report is due one week after the session. It must contain a description of the various measurements taken and an answer to all questions asked in the statement. Do not hesitate to include infrared images in the report to illustrate your point.

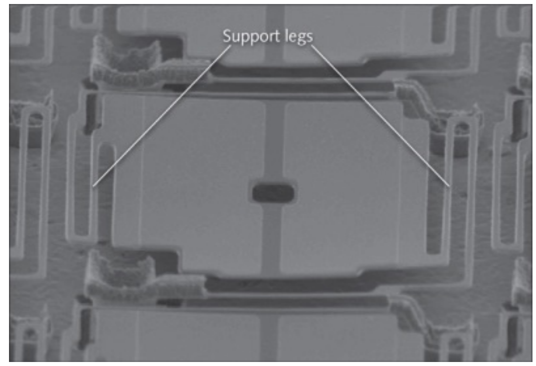


Figure 4.1: Left : Microbolometer Focal Plane Array (credit : www.ulis-ir.com). Right: a pixel (credit : http://www.laserfocusworld.com).

1 Objectives

At the end of this session, you should be able to:

- explain the importance of the emissivity in infrared thermography;
- explain the working principles of the bolometric camera;
- evaluate the performance of an infrared camera for thermography, this means to be able to:
  - identify the parameters of interest (NETD, spatial noise, MRTD, . . .);
  - propose procedures to measure such parameters;
  - evaluate the uncertainty of the measurements;
- evaluate the precision of the temperature measurements carried out by such a camera.

2 Presentation of the cameras

Be careful, infrared cameras are fragile and VERY expensive! Handle them with care...

You will use two microbolometer cameras of different generations. Their characteristics are given in Table 4.1. Remember that the NETD (noise equivalent temperature difference) is the smallest temperature difference detectable by the camera (assuming it observes a blackbody). It is often called "thermal sensitivity" by manufacturers, or "thermal resolution" (by abuse of language).

P1 Recall the working principle of a microbolometer focal plane array.

P2 Justify the choice of using the W as the flux unit in this lab (as opposed to s^{-1} or lumens).

	Camera AGEMA 570	Camera FLIR A655sc
Technology	microbolometer	microbolometer
Spectral band	$8 - 14$ µm	$8 - 14$ µm
Format	320×240 pixels	640×480 pixels
Pitch	50 µm	17 µm
Focal length	40 mm	24.6 mm
f-number	1	1
NETD @30 °C	< 150 mK	< 30 mK
Field of view (FOV)	$24° \times 18°$	$25° \times 19°$
Frame rate	2.7 Hz	50 Hz full frame

Table 4.1: Characteristics of the two cameras.

3 Reminders on the physics of an infrared scene

In general, the spectral luminance of any object X at temperature T is given by:

$$\left[\frac{dL}{d\lambda}\right]_{\text{X}}^{T}(\lambda) = \varepsilon(\lambda) \cdot \left[\frac{dL}{d\lambda}\right]_{\text{BB}}^{T} + \frac{\rho(\lambda)}{\pi} \cdot \frac{dE}{d\lambda}(\lambda), \tag{4.1}$$

where $\left[\frac{dL}{d\lambda}\right]_{\text{X}}^{T}$ is expressed in $\text{W} \cdot \text{m}^{-2} \cdot \text{sr}^{-1} \cdot \text{m}^{-1}$ (radiant units),
$\varepsilon(\lambda)$ is the emissivity of the object, which depends a priori on the wavelength, on the temperature of the object, on the surface roughness, etc,
$\left[\frac{dL}{d\lambda}\right]_{\text{BB}}^{T}$ is the spectral luminance of a blackbody at the same temperature,
$\rho(\lambda)$ is the diffuse reflection factor (also called albedo) of the object,
$\frac{dE}{d\lambda}$ is the spectral irradiance received by the object X coming from the environment.

This expression gives rise to two terms: the first one is the object's own luminance, proportional to that which would be emitted by a blackbody at the same temperature, the proportionality factor being the emissivity (ability of a material to radiate). This term is often referred to as an **emissive contribution**. The second term represents the diffuse reflection of ambient illumination, and is called the **reflective contribution**.

In the visible domain, the first term is negligible, and we find in the second term Lambert's law seen during the photometry course. In the infrared domain, we often tend to think that the first term is always dominant: we will see that this is not always the case.

It is interesting to note that at a given wavelength we always have: $\epsilon + \rho + \tau = 1$ (energy conservation, with τ the transmission factor of the object under consideration, and using the fact that the absorptivity α is equal to the emissivity ϵ second law of Kirchhoff)). Assuming that $\tau = 0$ (opaque material), we have: $\epsilon = 1 - \rho$. In addition, if we make the hypothesis that emissivity is independent of the wavelength in the spectral band of interest ($8 - 14$ µm in our case), we can rewrite 4.1 under the form:

$$L_{\text{X}}^{T} = \varepsilon \cdot L_{\text{BB}}^{T} + \frac{1 - \varepsilon}{\pi} \cdot E, \tag{4.2}$$

Materials with low emissivity (poor blackbodies)	Materials with medium emissivity	Materials with high emissivity (excellent blackbodies)
Polished gold: 0.01-0.1 Polished sheet of metal: 0.01-0.05 Polished aluminium: 0.04 Chrome: 0.1	Rusty aluminium: 0.2-0.4 Rusty sheet of metal: 0.3-0.5 Basalt: 0.7	Paint: 0.9-0.95 Wood: 0.9-0.95 Brick: 0.93 Concrete: 0.95 Cloth: 0.95 Paper (any color): 0.95 Human skin: 0.95-0.98

Table 4.2: Emissivity values in the $8 - 14\ \mu\mathrm{m}$ spectral band. Sources : Wikipedia.org, Raytek.fr, Woehler.com, Optris.fr.

where L^T_{X}, L^T_{BB} and E E are now integrated radiometric quantities in the $8 - 14\ \mu\mathrm{m}$ spectral band. This new formulation shows a "communicating vase" effect between the emissive and reflective contribution.

As an indication, Table 4.2 summarizes some emissivity values in the $8 - 14\ \mu\mathrm{m}$spectral band.

4 Getting started with the cameras

Each camera is connected to a computer equipped with suitable software: laptop + ThermaCam software for the AGEMA camera, and fixed station + ResearchIR software for the FLIR camera. A simplified manual of both softwares is available in the room.

⇝ Image the same area of the room with both cameras. Adjust the focus and choose a grey color scale for both cameras.

Q1 Compare qualitatively the images obtained (think in particular of observing how homogeneous areas of the scene are reproduced).

⇝ Present the available samples in front of the infrared camera: golden mirror, germanium window, ZnSe window, plastic cover, plexiglass plate, trash bag. Also observe a face (if possible with glasses) and the bulb of the desk lamp (lit, then turned off).

⇝ Save a few images showing:

- That a transparent material in the visible can be opaque in the infrared.
- that an opaque material in the visible can be transparent in the infrared.
- a thermal imprint, i.e. the trace left in the infrared by a hot element placed a few seconds on a cold element (or vice versa)
- an infrared reflection phenomenon

Q2 Comment on these images.

⇝ Measure the temperature of the palm of your hand.

Q3 Comment on the value obtained.

5 Influence of emissivity

In this part, only the FLIR camera is used.

There is a copper plate with two different surface treatments: left, matt black paint, and right, sandblasting. This plate is temperature controlled by a thermoelectric module.

⇝ Adjust the temperature of the copper plate to about $40\ ^\circ\mathrm{C}$ using the calibration chart available in the room. Image the copper plate by placing the FLIR A655sc camera at a distance of about 1m. Select two measuring zones in the left and right half of the copper plate respectively. Record the temperature for each measurement area and the raw signal.

Q4 Using the concept of emissivity, explain the observed temperature difference.

⇝ Set the plate temperature to approximately $20\ ^\circ\mathrm{C}$.

Q5 Why is there an inversion of contrast compared to the previous measurement? At which temperature does this contrast inversion occur ?

⇝ Measure again the temperatures displayed for each part of the plate.

Q6 Using equation (4.2), show that it is possible to estimate emissivity with the following formula:

$$\varepsilon = \frac{L_{\mathrm{right}}^{40\ ^\circ\mathrm{C}} - L_{\mathrm{right}}^{20\ ^\circ\mathrm{C}}}{L_{\mathrm{left}}^{40\ ^\circ\mathrm{C}} - L_{\mathrm{left}}^{20\ ^\circ\mathrm{C}}} \tag{4.3}$$

Q7 Deduce the emissivity value of sandblasted copper from your measurements.

Another method - empirical - to determine the emissivity of the sandblasted part is to modify the emissivity of this zone in the software so as to obtain the same temperature as the left part with an emissivity of 1.

⇝ Set the copper plate temperature to approximately $30\ ^\circ\mathrm{C}$. Using this method, determine a second measurement of the emissivity of sandblasted copper.

Q8 Compare with the first measurement. Which experimental parameter must be entered to correctly measure emissivity with this second method?

Q9 Based on the measurements in this section, what advice would you give to someone who wants to measure the temperature of metal elements?

6 Measuring the performance of infrared cameras

6.1 NETD measurements

The noise equivalent temperature difference (or NETD for Noise Equivalent Temperature Difference) indicates the **thermal sensitivity** of a camera, i.e. its ability to distinguish small temperature variations.

Suppose a camera observes a blackbody large enough to cover several pixels (see figure 4.2). By definition, the NETD of the infrared camera is the blackbody temperature difference that results in a signal variation equal to the standard deviation σ_s (rms) of the noise:

$$\Delta T = \text{NETD} \quad \text{si} \quad |V_{i,j}(T+\Delta T) - V_{i,j}(T)| = \sigma_s \tag{4.4}$$

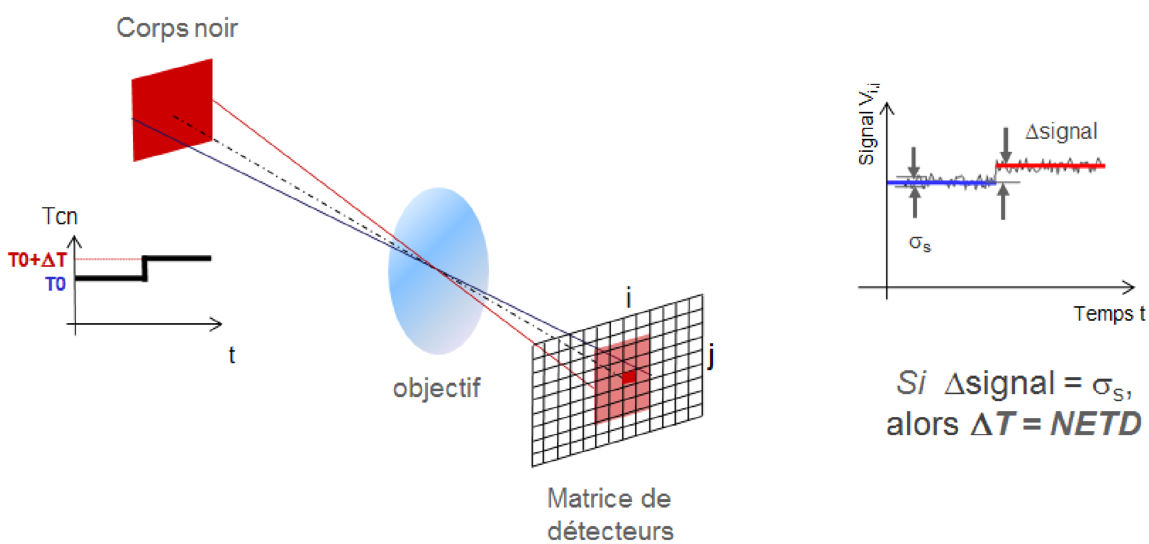


Figure 4.2: Illustration of the concept of NETD.

The NETD depends on the noise of the detector (NEP: Noise Equivalent Power, or flux equivalent au bruit in French) but also on the characteristics of the optics (in particular transmission and aperture number). The NETD is therefore a figure of merit of the camera as a whole (optics + detector).

⇝ In the rest of the lab session, we use the HGH blackbody (instead of the black-painted copper plate). If needed, a laminated user guide for the blackbody is available in the room. Set the blackbody temperature to 30 °C, making sure to wait until it has stabilized. On the blackbody image, define a temperature measurement point and a large area covering approximately half of the blackbody surface.

⇝ Record the temperature evolution measured in both zones over a period of 1 minute. Export the data to Excel.

Q10 Measure the standard deviation, and therefore the NETD, on the signal coming from the pixel alone. Do the values found correspond to the performance figures announced by the manufacturers? Why ?

In an imaging system, it is common to improve the signal-to-noise ratio using spatial averaging. Measure the standard deviation on the signal coming from the wide area, and therefore the new thermal sensitivity, always for a duration of 1 minute.

Q11 Shouldn't we see a greater improvement in the sensitivity? Suggest an explanation.

Q12 Why does the manufacturer announce a NETD value " at $30\ ^{\circ}\mathrm{C}$ " ? In other words, why does the NETD depend on the black body temperature ?

6.2 MRTD measurements

As noted above, the NETD quantifies only the camera's **thermal sensitivity**, without taking into account any limitations related to camera **resolution**. However, the scene observed by the camera may include high spatial frequencies (fine details), potentially poorly reproduced by the optics (if the fine details are smaller than the Airy spot) or by the detector array (if the fine details are smaller than the pixel size). This is where the **MRTD (Minimum Resolvable Temperature Difference)** comes in. It is measured by means of a differential blackbody equipped with a pattern of standardized shape, made up of 7 bars (or 3 cycles and a half) alternately cold and hot. The MRTD measurement is done by observing the disappearance of the bars of the test pattern in the image when the temperature difference becomes too small. The MRTD thus takes into account the scene (space-frequency composition), the monitor and the observer: it is a parameter representative of the complete optronic chain (and not just of the camera).

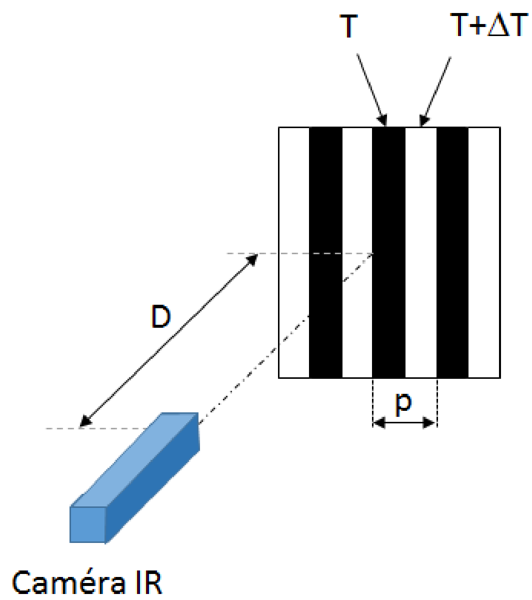


Figure 4.3: Principle of the MRTD measurement.

⇝ Position the target with different spatial periods ($p = \{5.0\text{ mm}; 2.0\text{ mm}; 1.0\text{ mm}; 0.8\text{ mm}\}$) in front of the blackbody. Adjust the blackbody setpoint temperature to $5\,°\text{C}$ above the target temperature (displayed in green on the blackbody controller). You can use the DELTA differential mode here. Place the FLIR camera 1 m from the target and adjust the focus. Lower the blackbody temperature in small steps (for example, in $0.5\,°\text{C}$ increments) until ambient temperature is reached. Carefully observe the target image and determine the blackbody temperature at the moment each target disappears: the MRTD is the difference between this temperature and the target temperature. Do not hesitate to vary the blackbody temperature using smaller steps (to obtain a more precise MRTD measurement) or larger steps (if you are still far from the MRTD).

⇝ Repeat the measurement for a distance blackbody - camera of $1,30\,\text{m}$, then $1,50\,\text{m}$.

Q13 Record the results on a graph. Choose the x-axis wisely ! It is recalled that the spatial frequency (in object space) is given by: $\nu = D/p$, where D is the black body - camera distance, and where p is the period of the target. If D is expressed in m and p in mm, ν is in cycles/mrad.

After characterizing the FLIR camera (measurements of NETD and MRTD), we propose to use it to discover two applications of infrared imaging: infrared thermography and non-destructive testing.

7 Absolute temperature measurement

Some applications of infrared thermography seek to detect local heating (e. g. thermal leak detection in buildings or predictive maintenance of electrical installations). In this case, the

NETD (or MRTD) are well suited figures of merit for estimating the performance of an infrared camera. In other applications, the absolute temperature of an object (e. g. for monitoring damage to mechanical parts in the aeronautical industry, or for monitoring the proper functioning of a nuclear fusion reactor) can be measured precisely. We are now interested in this type of applications, which require more performance. In this section, we try to estimate the accuracy with which the FLIR camera can perform an absolute temperature measurement.

Set the temperature of the blackbody to $60\ °\mathrm{C}$. Position the camera 60cm from the blackbody, and place a temperature measuring point in the middle of the blackbody (do not forget to indicate the emissivity and the reflected temperature !). Wait for the blackbody temperature to stabilize.

Q14 Knowing that the focal length of the lens is $24\,\mathrm{mm}$ and the pixel pitch is $17\ \mu\mathrm{m}$, what is the field of view of one pixel? What surface does this field correspond to at the level of the blackbody?

⇝ Insert the iris diaphragm between the blackbody and the camera (a few centimeters from the blackbody) and center it in relation to the temperature measurement point. Focus on the diaphragm. Perform a series of 4-5 temperature measurements for a diaphragm diameter ranging from $4\,\mathrm{mm}$ to full aperture.

Q15 Does the measured temperature vary according to the size of the diaphragm? Is this the expected result?

Q16 Compare any temperature variations observed with the previously measured NETD. Does NETD represent the accuracy with which it is hoped that an absolute temperature measurement can be achieved with this camera?

8 Non destructive testing (NDT)

In this section, we are interested in a particular application of infrared: non-destructive testing (NDT), which aims to highlight the presence of defects in the material by remote and non-contact measurement. Infrared imaging is thus used to detect defects in all kinds of materials, from composite materials used in aeronautics to agri-food products.

The principle of measurement is as follows: the surface of a sample is thermally excited and its surface temperature changes as a function of time. It is possible to show defects in the volume of the material.

Industrial NDT systems offer flash or halogen lighting, and the sensitivity of the sample to excitation can be observed in reflection (measurement on the front side) or transmission (measurement on the backside). In the framework of this lab, lighting is done with 400W halogen lamps and observation on the front side.

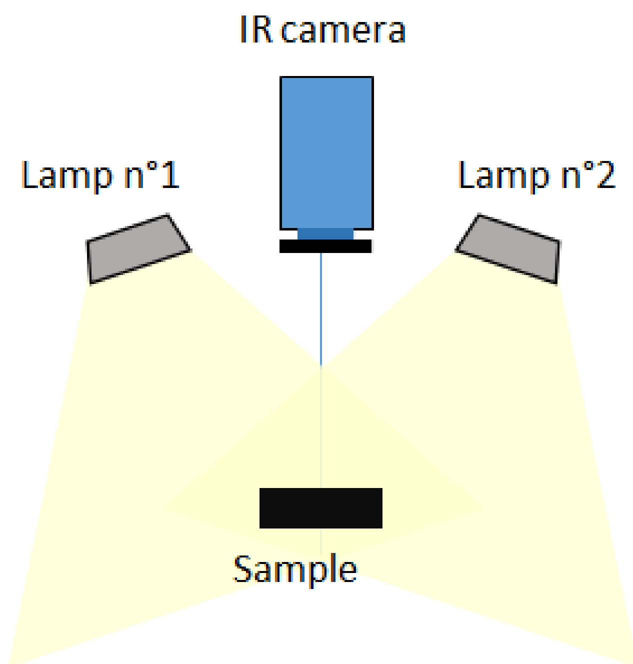


Figure 4.4: Experimental configuration used in this lab : excitation with halogen lamps, and front side observation.

⇝ Position the two small frames in front of the camera (be careful with the thermal imprints you will leave when touching the objects!).

⇝ Take a first infrared image of the two frames before lighting them. Turn on the halogen lamps for 10-15s and take a second image.

Q17 What are you observing? What do you deduce from this on the internal structure of the two objects?

⇝ Now place the cardboard-covered sample (the cardboard side towards the camera) in front of the camera.

⇝ Illuminate the sample for one minute and record the resulting infrared image.

Q18 Comment on it.

⇝ Turn the sample over and illuminate the other side again for one minute.

Q19 What are you observing?

Annexe 1: Blackbody law

We recall for the record the law of the black body (Planck's law) seen during radiometry course:

$$\left[\frac{dL_e}{d\lambda}\right]_{\mathrm{BB}}^{T} = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda k_{\mathrm{B}} T}} - 1} \tag{4.5}$$

where $\left[\frac{dL_e}{d\lambda}\right]_{\mathrm{BB}}^{T}$ is expressed in $\mathrm{W} \cdot \mathrm{m}^{-2} \cdot \mathrm{sr}^{-1} \cdot \mathrm{m}^{-1}$, T is the blackbody temperature in K, λ l is the wavelength in m, $c = 3 \times 10^8\ \mathrm{m/s}$, $h = 6,63 \times 10^{-34}\ \mathrm{J} \cdot \mathrm{s}$ (Planck's constant) , and $k_{\mathrm{B}} = 1,38 \times 10^{-23}\ \mathrm{J/K}$ (Boltzmann's constant). As an example, we can compare this spectral luminance for various temperatures between 295 K and 315 K, *i.e.* $22°\mathrm{C}$ and $42°\mathrm{C}$

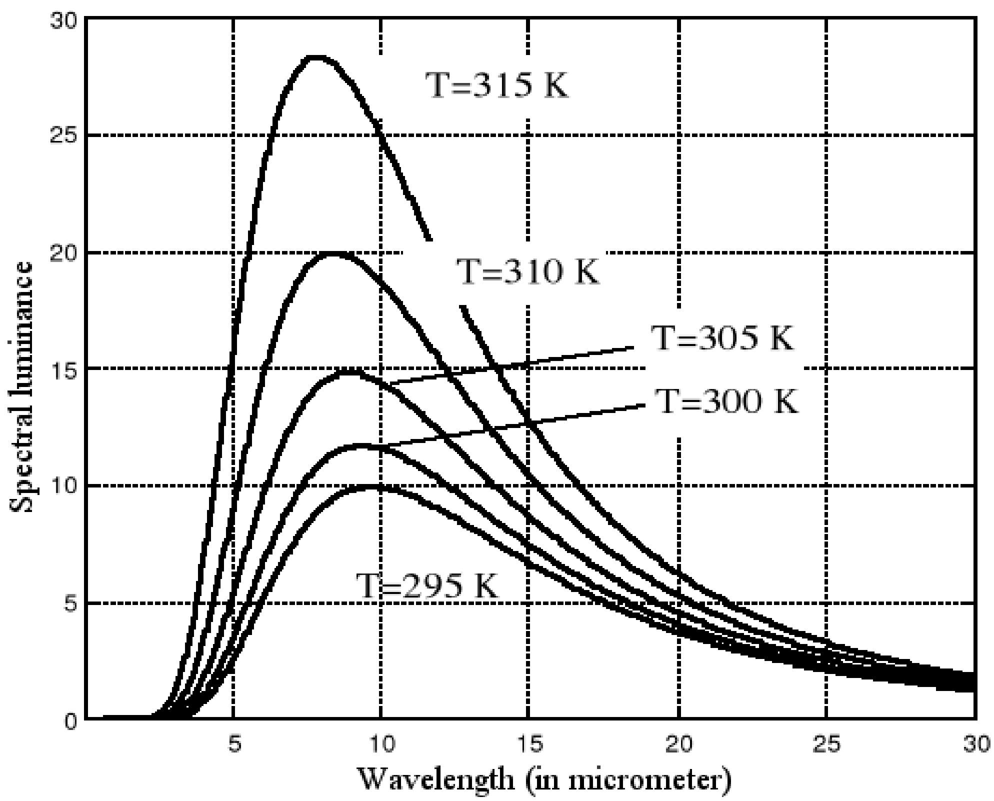


Figure 4.5: Spectral luminance of a black body (in $\mathrm{W} \cdot m^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$) as a function of wavelength, for various temperatures.

We see that the flux emitted from a black body increases with its temperature. The camera's bolometer is a thermal detector : it is sensitive to the incident power. Its sensitivity can be supposed constant on the IR band III (8-14 μm). The transmission of the lens can as well be considered as constant over this band. With those hypothesis, the video signal obtained from the image of a black body of temperature T is :

$$v(T) = K. \int_{8\mu\mathrm{m}}^{14\mu\mathrm{m}} \frac{dL}{d\lambda}(\lambda, T)\, d\lambda$$

The following curve shows the result of the computation of this integral for a temperature varying between 275 K and 325 K (approximately 0°C to 50°C)

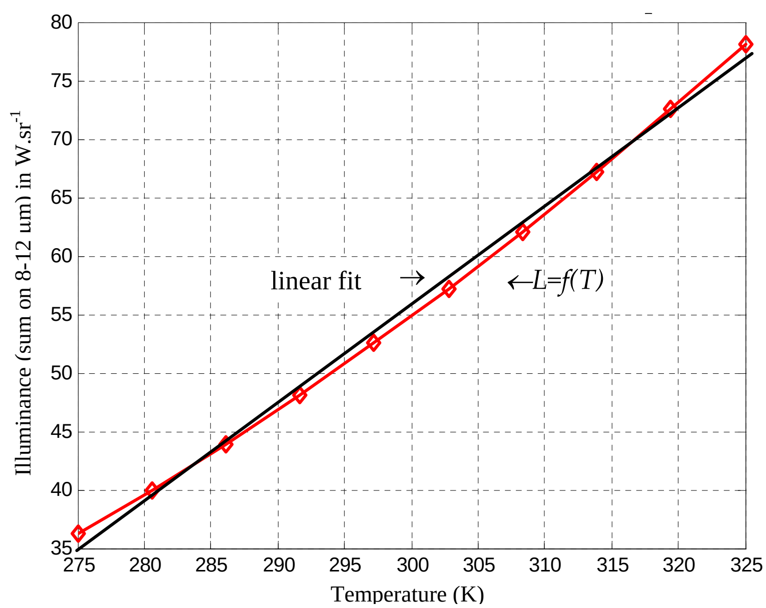


Figure 4.6: Total illuminance of the source, on the 8-12 μm band, as a function of its temperature.

We see that the hypothesis of a linear variation of the video signal with regard to the temperature is not realised. However, the error remains small on this limited temperature range of 20 to 40 °C.

Annexe 2 : MRTD measurement

We can show that the MRTD reads:

$$MRTD(\nu) = K\frac{NETD}{FTM_{\text{global}}(\nu)}, \tag{4.6}$$

where K is a constant and where the overall MTF of the camera is the product of the optical and detector transfer functions by a $S(\nu)$ function that accounts for the spatial response of the monitor and the eye (in all honesty, it is difficult to define a transfer function for the eye because it is non-linear):

$$FTM_{\text{global}}(\nu) = FT_{\text{opt}}(\nu) \cdot FT_{\text{det}}(\nu) \cdot S(\nu) \tag{4.7}$$

In the rest of this annexe, the $S(\nu)$function will be ignored.

It is recalled that the transfer function of an optics limited by diffraction (without aberrations or errors of realization, with a circular pupil) is given by:

$$FT_{\text{opt}(\nu)} = \frac{2}{\pi}\left[\arccos\left(\frac{\nu}{\nu_{\text{c,opt}}}\right) - \frac{\nu}{\nu_{\text{c,opt}}}\sqrt{1-\left(\frac{\nu}{\nu_{\text{c,opt}}}\right)^2}\right], \tag{4.8}$$

where ν is the spatial frequency (in image space) and $\nu_{\text{c,opt}}$ is the cutoff frequency of the optics (also in image space), given by: $\nu_{\text{c,opt}} = \frac{1}{\lambda N}$.

In the hypothesis of a square pixel of a given pixel size, the detector MTF is given by:

$$FT_{\text{det}(\nu)} = \frac{\sin\left(\pi\frac{\nu}{\nu_{\text{c,det}}}\right)}{\pi\frac{\nu}{\nu_{\text{c,det}}}}, \tag{4.9}$$

where $\nu_{\text{c,det}}$ is the cutoff frequency of the detector (in image space): $\nu_{\text{c,det}} = \frac{1}{\text{pixel size}}$.

For the FLIR camera, the optics and detector modulation transfer functions are plotted in 4.7, along with the MRTD curve. This one grows with the spatial frequency, until reaching a vertical asymptote corresponding to the detector's cut-off frequency: this being lower than the optic's cut-off frequency, it is therefore the pixel size that limits the camera's resolution.

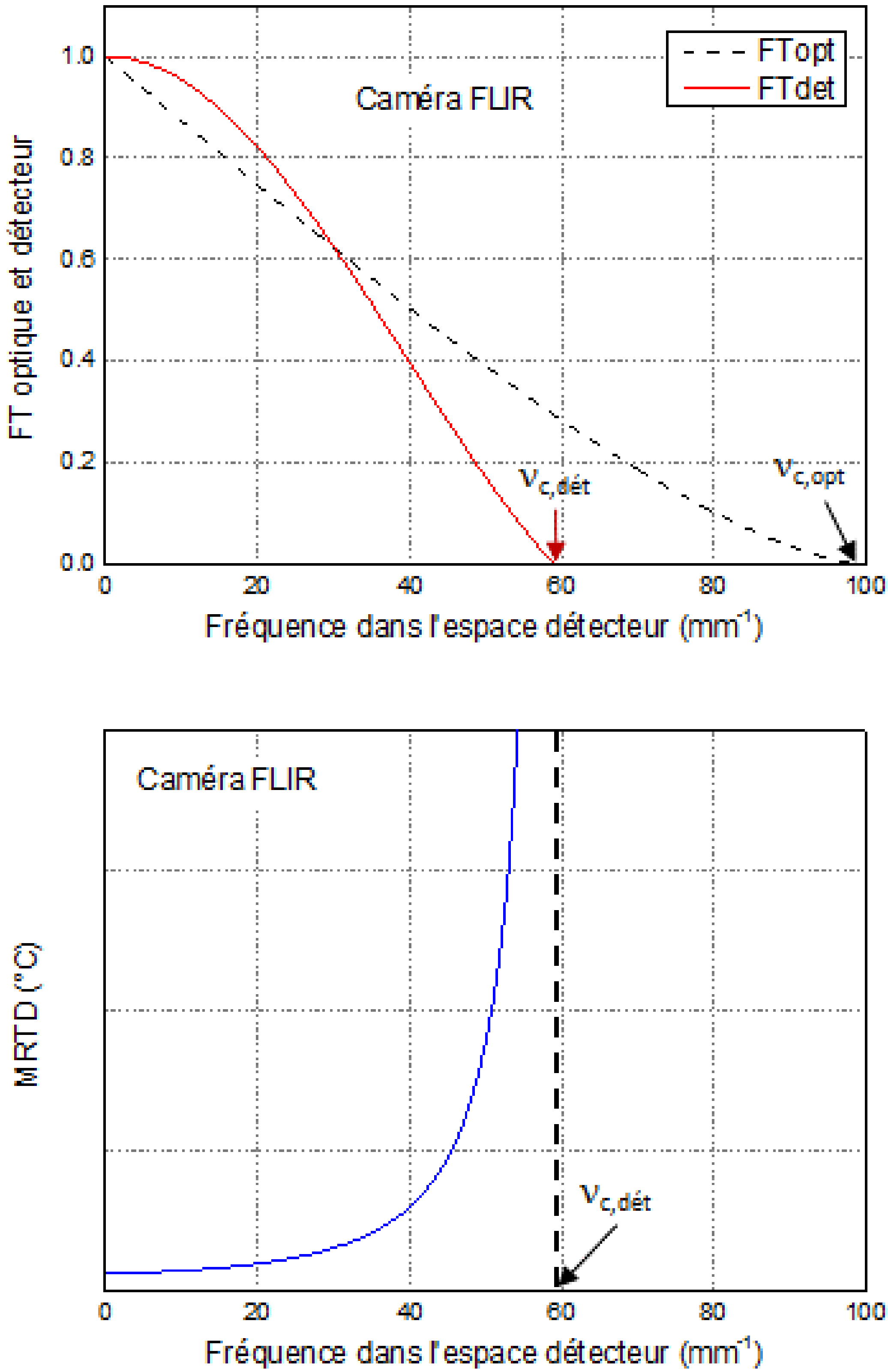


Figure 4.7: Upper panel : MTF of optics and detector, for the FLIR camera ; lower panel : MRTD of the FLIR camera. The vertical asymptote corresponds to the cutoff frequency of the detector.

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Grille d'évaluation de la qualité des compte-rendus de TP - Cycle Ingénieur 2ème année

Critère	Eléments observables	Manifeste		Attendu		Perfectible	Non observable
Problématique et démarche	Énoncé de la problématique	☐	Problématique claire, présentée dans l'introduction, rappelée dans le corps du document et dans la conclusion.	☐	Problématique présentée dans l'introduction	☐	☐
				☐	et reprise dans la conclusion	☐	☐
	Structure du document	☐	Plan apparent et pertinent. Démarche bien mise en évidence.	☐	Plan apparent (paragraphes numérotés et hierarchisés)	☐	☐
	Contenu	☐	Des résultats supplémentaires sont présentés dans le document. Présence de schémas/ dessins/photos réutilisables.	☐	Toutes les mesures et tous les réglages effectués en séance sont décrits dans le document.	☐	☐
				☐	Toutes les courbes et figures ont un titre et sont citées dans le corps du texte.	☐	☐
				☐	Les éventuels éléments externes sont clairement crédités.	☐	☐
	Cohérence de l'exposé	☐	Cohérence et rigueur de l'introduction, de la conclusion et des paragraphes d'analyse des résultats.	☐	Fil conducteur rigoureux, apparent.	☐	☐
Mesures et réglages	Relevés expérimentaux	☐	Motivation argumentée des protocoles utilisés. Présentation des réglages et/ou des mesures brutes avec leur incertitudes	☐	Présentation précise : des protocoles suivis,	☐	☐
				☐	des mesures brutes avec leur incertitudes, et/ou des réglages.	☐	☐
	Eléments de preuve	☐	Présence d'éléments de preuve (copie d' écran, photos, etc) en nombre adapté.	☐	Présence de quelques éléments de preuve (copie d'écran, photos, etc).	☐	☐
	Traitement des mesures	☐	Justification argumentée du choix des traitements éventuels des données.	☐	Traitement éventuel des mesures explicité dans le texte.	☐	☐
	Incertitudes de mesures			☐	Evaluation justifiée des incertitudes de mesure	☐	☐
Analyse	Résultats	☐	Résultats de mesure corrects ou pointage et analyse des erreurs manifestes	☐	Résultats de mesure corrects ou pointage des erreurs manifestes.	☐	☐
				☐	Courbes éventuelles au format scientifique (axes, unités, légendes, titre, incertitudes, courbes de tendance).	☐	☐
	Modèle	☐	Comparaison argumentée à un modèle.	☐	Eléments de comparaison à un modèle	☐	☐
	Critique	☐	Critique argumentée du protocole et du modèle	☐	Eléments de critique du protocole ou du modèle	☐	☐
	Erreurs	☐	Analyse des erreurs commises	☐	Pointage des erreurs commises.	☐	☐
Conclusion	Synthèse	☐	Paragraphe de conclusion reprenant les principaux résultats et leur apport à la problématique et présentant des perspectives	☐	Paragraphe de conclusion reprenant les principaux résultats	☐	☐
		☐		☐	et leur apport à la problématique	☐	☐
	Bilan des acquis d'apprentissag	☐	Acquis d'apprentissage listés et comparés à ceux visés par la séance	☐	Acquis d'apprentissage listés	☐	☐
Format		☐	Document synthétique (nombre de pages limité).	☐	Nom des membres du binôme, numéro de binôme, titre du TP présents sur la première page.	☐	☐
				☐	Nom du fichier respectant le format demandé. Nombre de pages inférieur à 10.	☐	☐
				☐	Nombre de pages inférieur à 10.	☐	☐