Introduction course to master lab practice

Contents and evaluation of the lab-practice course

Contents

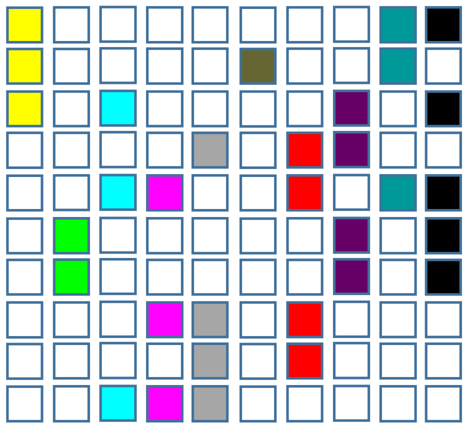
These lab-practice courses have two aims:

1) Give a common background in all **basic fields of optics** and some other *useful neighboring fields*: **Ray optics**, **interferences**, **diffraction**, **spectroscopy**, *metrology and electronics*, *numerical simulation*, *data analysis by computer*.
2) Get you in touch with old and new opto-mechanical elements and train a bit of your alignment skills

List of experiements

1. Geometrical optics
2. Raytracing with Oslo
3. Fourier optics
4. Polarization
5. Monochromator
6. Michelson interferometer 1
7. Michelson interferometer 2
8. Spectroscopy
9. Photodetectors
10. Holography

Trained skills



Depending on your background your perception of the lab work units can be very different. Students who need to catch up in terms of working methodology and or knowledge… do it!

Required working methodology and evaluation

You will not be able to repeat a lab if you went home without having good data:

- ➔ Prepare the lab sessions. At the beginning of each lab description there are keywords to help you with preparation.
- ➔ Be ready to start analyzing your data during the lab session. (If necessary, repeat partially.)
- ➔ Consider that not all answers to the questions in the lab work descriptions are found during the lab practice. The answers to the remaining questions should be found using your prior knowledge, your other courses, books, reliable internet sites… thus your preparation notes (see example lab-book entry mentioned below).

You need to write a close-to-perfect report on *one* lab, which will be chosen *after* the sessions:

- ➔ Take detailed notes in your personal lab book. (This is also a training for industry research.)
  - o We suggest a standard A4 workbooks with 96 pages (1 per student).
  - o The lab book will be evaluated (20% of final mark)
  - o There is a good example entry available on Ametice and on https://www.fresnel.fr/perso/wagner/enseignement%20anglais.htm. The example entry refers to the lab description given at the beginning of the example of a good lab report available on the same page.
  - o The lab book mark will also be influenced by your behavior during the sessions (comes prepared or not, tidies up after experiment, thinks before asking but does not remain silent when having problems…)
- ➔ Read the example lab report with structure and formatting indications. It is available on Ametice and on https://www.fresnel.fr/perso/wagner/enseignement%20anglais.htm.
  - o The report will be evaluated (40% of final mark).
  - o The report has to be close to perfect in about 15 pages (handwritten) or 10 pages (printed).
  - o You can find indications on the report structure in the appendix.

You need to be able to discuss with us about all experiments, stating with the one you did the report for:

- ➔ Push the analysis of the measurements far enough to learn something. (Typically one passes at least the same time at home as in the lab.)
- ➔ We will try to organize an oral exam (40% of the final mark)
  - o Make sure you understood all lab works and the links between them

Organizational questions

These lab works comprise 10 lessons of 4 hours each on Thursday afternoon. As you are 13 groups there are some Thursday afternoons that are free. Completely arranged exchanges may be possible on demand.

For every lesson, bring with you

<u>Lab book:</u>

We will check that you prepared the labwork and, at the end, that the measurements are not completely wrong and then sign the measurement protocol. If this experiment is chosen for the report, you need to include photocopies of your original signed measurement protocol in the report. See also the example lab book entry available on Ametice and on https://www.fresnel.fr/perso/wagner/enseignement%20anglais.htm

USB memory stick for data. (Does not replace the lab book.)

Planning

Titles and numbers of the 10 lessons:

1	Geometrical optics	6	Michelson interferometer 1
2	Raytracing with Oslo	7	Michelson interferometer 2
3	Fourier optics	8	Spectroscopy
4	Polarization	9	Photodetectors
5	Monochromator	10	Holography

Planning: The table below tells you when you will do which lesson.

The table gives the lesson number a certain group will do at a certain date

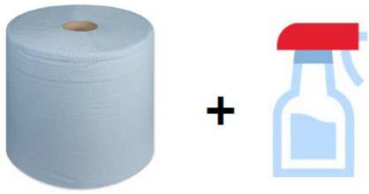
	Groups												
Dates	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
October 8, 2020	1	2	3	4	5	6	7	8	9	10			
October 15, 2020	2	3	4	5	6	7	8	9	10				1
October 22, 2020	3	4	5	6	7	8	9	10				1	2
October 29, 2020													
November 5, 2020	4	5	6	7	8	9	10				1	2	3
November 12, 2020	5	6	7	8	9	10				1	2	3	4
November 19, 2020	6	7	8	9	10				1	2	3	4	5
November 26, 2020	7	8	9	10				1	2	3	4	5	6
December 3, 2020													
December 10, 2020	8	9	10				1	2	3	4	5	6	7
December 17, 2020	9	10				1	2	3	4	5	6	7	8
December 24, 2020													
December 31, 2020													
January 7, 2021	10				1	2	3	4	5	6	7	8	9
January 14, 2021				1	2	3	4	5	6	7	8	9	10
January 21, 2021			1	2	3	4	5	6	7	8	9	10	
January 28, 2021		1	2	3	4	5	6	7	8	9	10		
February 4, 2021													
February 11, 2021	orals	orals	orals	orals	orals	orals	orals	orals	orals	orals	orals	orals	orals

How to avoid contamination (hopefully)

1. No access to the lab works without mask over nose and mouth at all times!

2. Before touching anything else clean your hands. Sanitizer gel is provided.

3. To disinfect your setup buttons and work area:
    a. Take sufficient paper towel.
    b. Spray disinfectant on it (NOT one optical elements)
    c. Go to your setup and (with instruments switched off) clean buttons and work area.



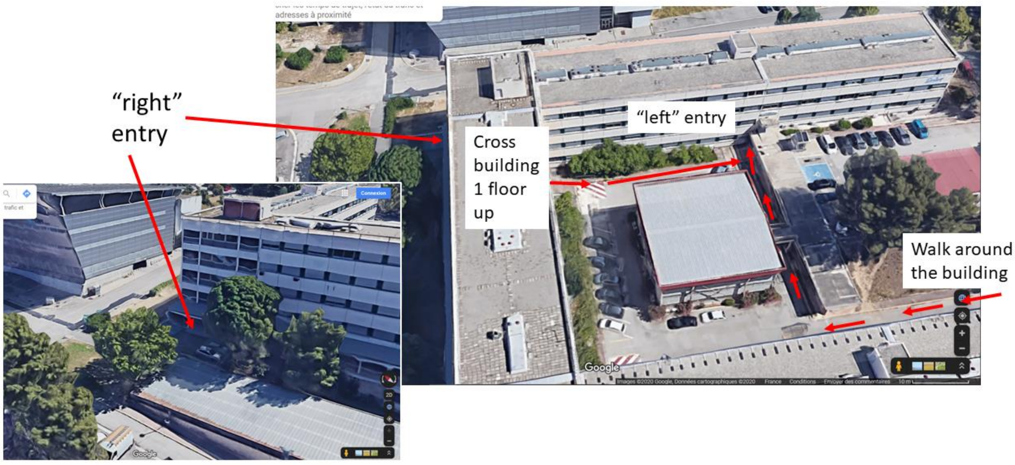
Additionally, we will ventilate the room by opening all doors and windows before, in the middle and after the session. Take care, wind can be strong here. So, fix your papers during venting.

If possible, we will leave at least one or two windows open during the session. It might be cold.

All students are expected to keep a distance of 1.5 m between them. This is more or less possible in the lab room.

Where to go?

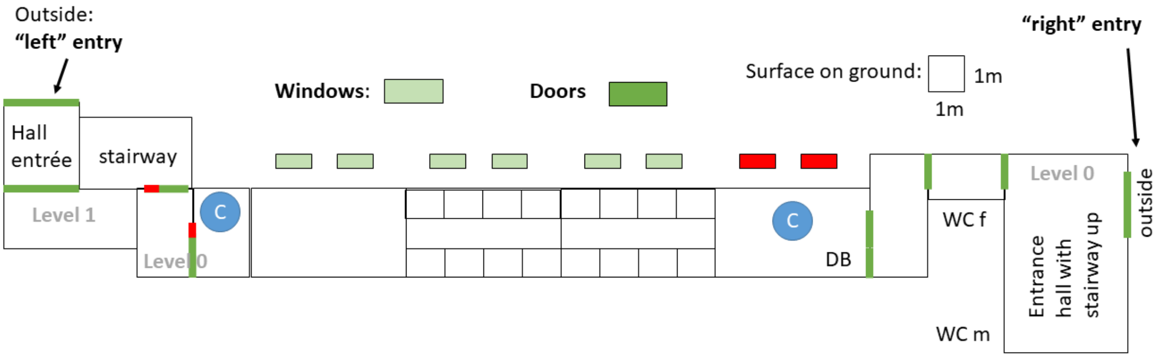
There are two entries to the lab work room in “aile 1”. Best use the left entry if you do lab number 1, 3, 4, 5 or 9. (Geometrical optics, Fourier optics, Polarization, Monochromator, Photodetectors)



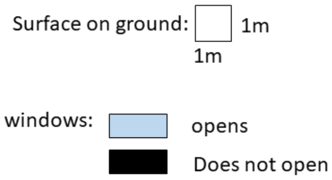
Room geometry and air flow

C Cleaning station

1. Use hand sanitizer
2. Take sufficient paper towel
3. Spray disinfectant on the paper towel (do not spray on optical elements)
4. Go to your setup and wipe buttons and surfaces you want to touch



Setup positions



1 Geometrical optics
2 Raytracing with Oslo
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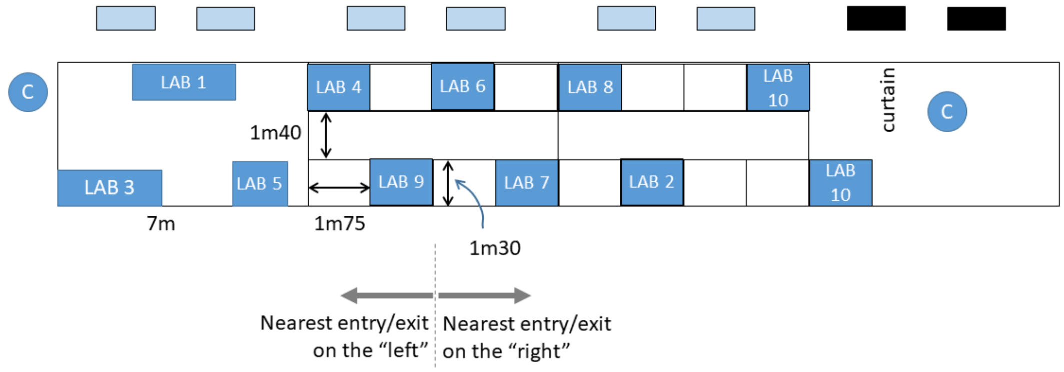


Contact person:

Frank WAGNER,

Room 217, Institut Fresnel

frank.wagner@fresnel.fr

Communicating on measurements

The lab practice is also training for performing measurements and communicating on measurements.

Let's make an exercise!

Don't think about students, teachers, marks (or other school stuff).

Think about Airbus asking a small specialized company you work for to develop a new detector for their planes. (Or imagine other aims in the scientific field.)

We need *precise communication* about *quantified technical specifications* in order to create a base for decisions.

So, which measurement is the best one?

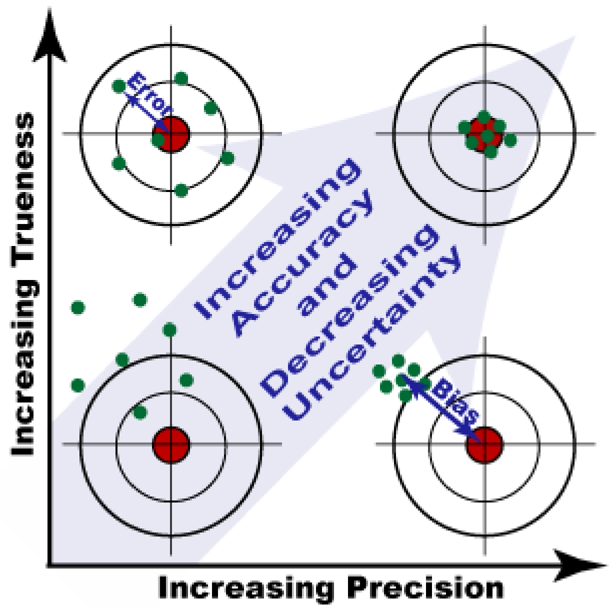
What other information is needed? (Besides the results of the measurements.)

The problem with the two rulers:

Good **precision** is linked to good **repeatability** or good **reproducibility**. Both are measured by **statistical uncertainties (statistical errors)**.

Trueness describes the proximity of the mean of a measurement set to the true value. The **deviation** from the true value is also named **bias**. Deviations from the true value may be linked to **systematic errors**.

Accuracy consists of simultaneous *Trueness and Precision* (According to ISO 5725-1)



→ **Calibration** of instruments, metrology...

Repeating a measurement allows to quantify the statistical uncertainties.

A measurement without statistical uncertainty (which is linked to the measurement method) makes no sense.

Also, whenever possible compare your results to reference values (check the trueness, calculate the relative deviation and discuss it in comparison with the statistical uncertainty and possible systematic errors of the measurement).

Formulas for statistical uncertainties

Again: *A measurement without uncertainty has no sense!* Mention which kind of uncertainty is the dominating one: experimental precision, scale precision, statistical (repeatability), discuss possible systematic errors.

The following formulas for statistical uncertainties are based on a normal distribution (Gaussian statistics):

Uncertainty of the average (or mean):

If you have taken n measures of values x_i (with i from 1 to n).

The average (or mean) is given by $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$

The empirical standard deviation of the measurement is: $\sigma = \sqrt{\frac{1}{n-1} \cdot \sum_{i=1}^{n} \left(x_i - \bar{x}\right)^2}$

σ increases with increasing n and can thus not be used without adjustment to describe the statistical uncertainty. **The *standard error* $\Delta\bar{x}$ of the average is:** $\Delta\bar{x} = \frac{\sigma}{\sqrt{n}}$

For $n > 10$, one expects, independently of the precise value of n, to find 68% of the values x_i in the interval [$\bar{x} - \Delta\bar{x}$, $\bar{x} + \Delta\bar{x}$].

(Remarks: - The interval with ± $2\Delta\bar{x}$ corresponds to a confidence of close to 95%.
- For less than 10 measurements one should multiply by the Student *t*-factor)

Calculating an uncertainty with student t-factor correction in Excel (French version):

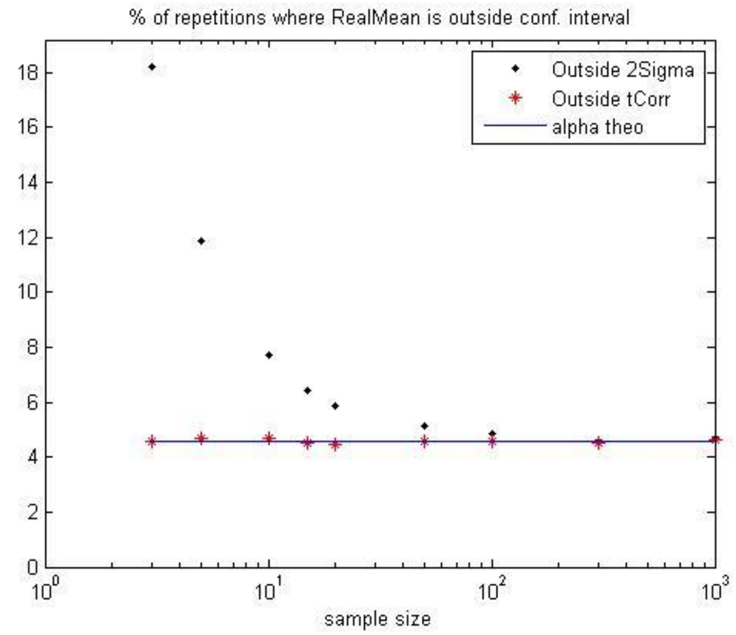
Choose confidence of interval: C (for example = 0.683 or 0.95), Values are in the cells of ValueRange:

```
= ECARTYPE(ValueRange)/RACINE(NB(ValueRange)) *
        LOI.STUDENT.INVERSE(1 - C ; NB(ValueRange)-1)
```

The same thing in Matlab: `nbMeas` is the number of measurements in the set of values `V`.

```
= std(V) ./ sqrt(nbMeas).* tinv( 1 - (1-C)/2 , nbMeas-1 )
```

It may be interesting for you to make a Monte-Carlo like Matlab (or the free version Octave or Python or whatever) program to check these formulas. For comparison, I put something on my web page: Monte-Carlo for uncertainties of mean, bootstrapping and weighted means (http://www.fresnel.fr/perso/wagner/enseignement%20anglais.htm)



Error propagation

If one calculates a value *r* starting from measured values *a* and *b* (mean $\bar{b}$ and uncertainty Δb) and using a function *r* = *f*(*a*, *b*), one calculates the standard error of *r* using the relationship:

$$\Delta r = \sqrt{\left(\left. \frac{\partial f(a,b)}{\partial a} \right|_{\substack{a=\bar{a} \\ b=\bar{b}}} \cdot \Delta a \right)^2 + \left(\left. \frac{\partial f(a,b)}{\partial b} \right|_{\substack{a=\bar{a} \\ b=\bar{b}}} \cdot \Delta b \right)^2}$$

($\bar{a}$, Δa, $\bar{b}$, Δb and $\bar{r} = f(\bar{a}, \bar{b})$ are known.)

Library of essential cases: → *Handwritten pages*

Reading a difference (or a sum) r = a – b

Multiply by a constant r = c * a, c = const.

Factors and powers: $r = a^c * b^d$, c and d = const.

(Special case: Calculating a ratio: r = a/b, ATTENTION if a = 0 is possible)

In all other cases you need to redo the calculation

Weighted average

The formula for an average of measurements for which you know that some are more precise than others (weighted average) is $\bar{x}_w = \sum_{i=1}^{n} w_i\, x_i \Big/ \sum_{i=1}^{n} w_i$. The weights w_i are $w_i = \frac{1}{(\Delta x_i)^2}$, where Δx_i is the student-t corrected error of the value x_i.

The error of the weighted average can then be found using the error propagation formula $\Delta\bar{x}_w = 1 \Big/ \sqrt{\sum_{i=1}^{n} w_i}$.

Significant numbers in the results

If the measurement was repeated only a few times, use only one significant number in the uncertainty: (this is the usually teached rule.)

Example: $\overline{m}$ = 125.0481 g and $\Delta\overline{m}$ = 0.1431 g is presented in the report as: m = 125.0 ± 0.2 g

Using this rule on may communicate an uncertainty of nearly 200% of the calculated uncertainty (0.105 → 0.2: 190%). Personally *I thus prefer to keep 2 significant digits in the communicated uncertainty* (maximum of 110%):

Example: $\overline{m}$ = 125.0481 g and $\Delta\overline{m}$ = 0.1431 g is presented in the report as: m = 125.05 ± 0.15 g

(Note that the value is rounded but the uncertainty is always approximated by the next larger value.)

(Linear) regression or fitting of theoretical curves to experimental data

Often theoretical curves can be compared to experimental data in order to validate the theory or to determine certain parameters of the theory. A number of curve-fitting programs exist for this purpose (Origin (qti-plot), Igor, (Matlab, Excel)) and the better ones allow to freely define the expression for the theoretical curve. They also give you the uncertainties of the parameters together with the best values.

In case you have a linear relationship, there exist analytical formulas allowing to calculate the best slope and the best offset of the straight line as well as their uncertainties:

During the measurement you obtain *n* pairs of values (x_i ,y_i), with *i* from 1 to *n*, which form approximately a straight line: *y* = *m x* + *b*.

The best parameters *m* and *b* are:

$$m = \frac{n\sum x_i y_i - \sum x_i \cdot \sum y_i}{n\sum x_i^2 - \left(\sum x_i\right)^2} \qquad \text{and} \qquad b = \frac{\sum x_i^2 \cdot \sum y_i - \sum x_i \cdot \sum x_i y_i}{n\sum x_i^2 - \left(\sum x_i\right)^2}$$

Their 68%-confidence uncertainties (which equal in this case the standard deviations) are:

$$\Delta m = \sigma_m = \sqrt{\frac{n\sum(y_i - b - mx_i)^2}{(n-2)\left(n\sum x_i^2 - \left(\sum x_i\right)^2\right)}} \quad \text{and} \quad \Delta b = \sigma_b = \sqrt{\frac{\sum x_i^2 \cdot \sum(y_i - b - mx_i)^2}{(n-2)\left(n\sum x_i^2 - \left(\sum x_i\right)^2\right)}}$$

In Excel or OpenOffice Calc you can use the function « droitereg » (name in the French version). It's a matrix function which outputs the parameters *m* and *b* (first row), the 68%-confidence uncertainties (second row) and the coefficient of determination R^2 (left of third row). In Excel you should thus select a region of 2 columns and 3 rows, write = droitereg(Ymeasurements ; Xmeasurements ; vrai ; vrai) and push <ctrl> + <shift> + <enter> simultaneously.

(Qti-plot is free software and you can copy it from the computers in the lab.)

Graphical representations

Graphs are used to present a series of measurements and illustrate their agreement with a model. **Measurements are represented as 'points' (markers)** that ideally have horizontal and vertical error bars indicating the uncertainty of each measurement. (Fitted) **model curves are represented as solid lines**.

Graphs have two axes with a caption that includes the unity of the values. At least three labels are needed to see if the scale is linear or not.

Each figure has a caption that describes the graph(s) of the figure. The figure caption should rather detailed in order to ne understandable independently for a reader from the field.

SEE THE GRAPHS IN THE "COMMENTED EXAMPLE OF A GOOD LAB REPORT" which is downloadable on Ametice and on my teaching page:
http://www.fresnel.fr/perso/wagner/enseignement%20anglais.htm

APPENDIX

<u>Structure of the detailed report:</u> (Please see also the example report)

The detailed report is only asked for one experiment, which we will chose after looking through your lab book. It should contain the following sections:

1. Introduction

   At least one sentence on the aim of the lesson

2. Theory

   A short summary of the *useful* theory. Formulate yourself, no copy/paste accepted.

3. Description of the (measurement) procedure

4. Preparation of the experiment

   From the formulas in the theory section, derive the formulas that you will use for the data analysis.

5. Data, data analysis and presentation of the results

   Include lab book photocopies here, do not forget to calculate the statistical uncertainties and make nice meaningful graphs representing your data and its analysis.

6. Discussion

   Quantitative comparison to the theoretical values; discussion of possible systematic errors or uncertainties; Comments.

7. References

   List books, websites and other resources you used.