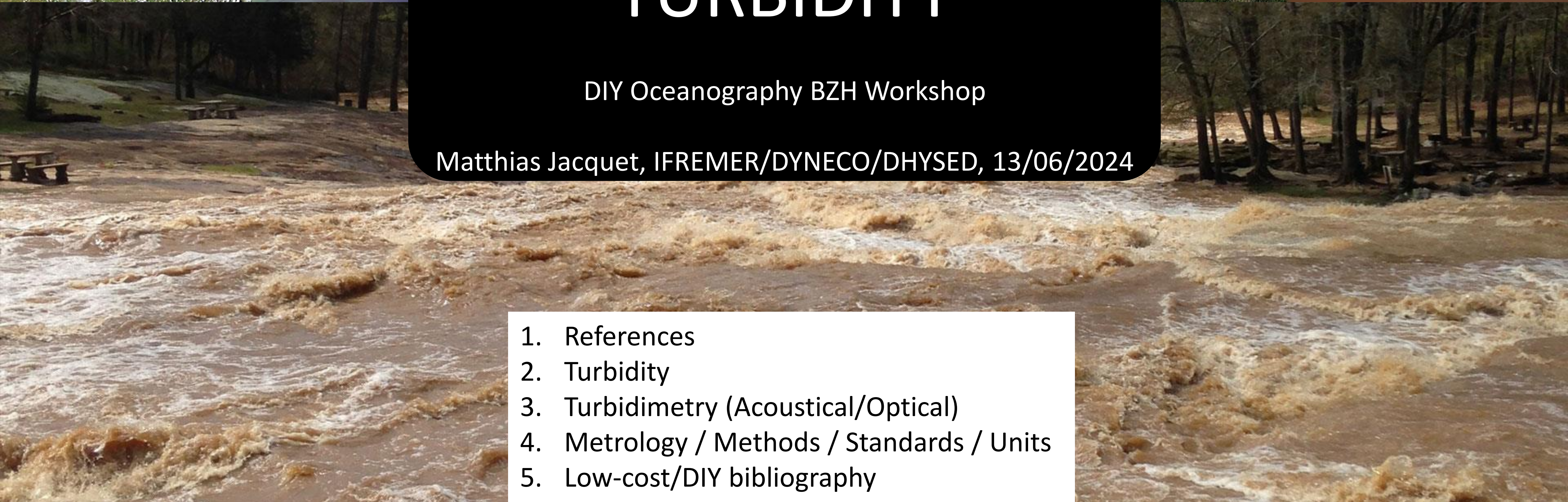


TURBIDITY

DIY Oceanography BZH Workshop

Matthias Jacquet, IFREMER/DYNECO/DHYSED, 13/06/2024



1. References
2. Turbidity
3. Turbidimetry (Acoustical/Optical)
4. Metrology / Methods / Standards / Units
5. Low-cost/DIY bibliography

References

Book :
Les capteurs en instrumentation industrielle, G. ARSCH, Dunod

Paper :
Kitchener et al. – 2017 – A review of the principles of turbidity measurement

PhD :
Tessier, C. (2006). *Caractérisation et dynamique des turbidités en zone côtière: l'exemple de la région marine Bretagne Sud* (Doctoral dissertation, Université de Bordeaux 1).

Web :
https://www.fondriest.com/environmental-measurements/parameters/water-quality/turbidity-total-suspended-solids-water-clarity/
https://femto-physique.fr/index.html

Turbidity

Wikipedia

La **turbidité** désigne la teneur d'un fluide en matières qui le troublent. Dans les cours d'eau, elle est généralement causée par des matières en suspension et des particules colloïdales qui absorbent, diffusent ou réfléchissent la lumière. Dans les eaux eutrophes, il peut aussi s'agir de bactéries et de micro-algues. Quand un fleuve turbide se jette en mer, il crée généralement un bouchon vaseux, un delta sédimentaire et produit en mer un « éventail turbiditique »[2] parfois bien visible depuis un satellite.

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La turbidité fait référence à la diminution de la clarté de l'eau causée par la présence de matières suspectes, qui absorbent ou diffusent la lumière descendante.

Lorsque la concentration des particules suspectes devient perceptible, l'eau est considérée comme trouble.

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Le Petit Larousse 2022

1. Etat d'un liquide trouble : *La turbidité d'un vin*.
2. **HYDROL.** Teneur en troubles, en boues, etc, d'un cours d'eau.
3. **Courant de turbidité** [océanol.], violent courant sous-marin qui transporte une grande quantité de matériaux en suspension et qui s'écoule sur le lit des canyons en traversant des couches de densité moindre.

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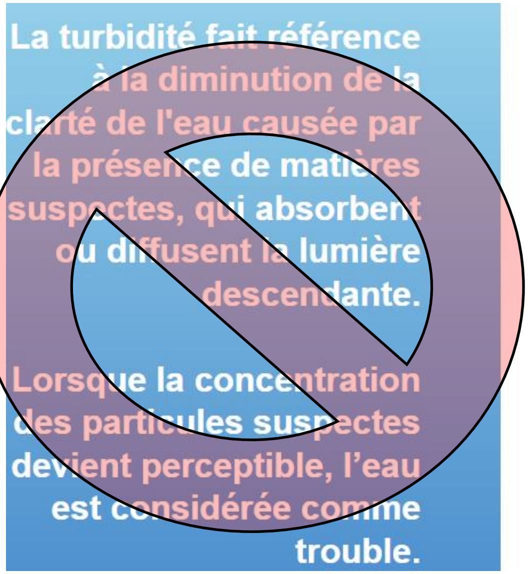

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Wikipedia

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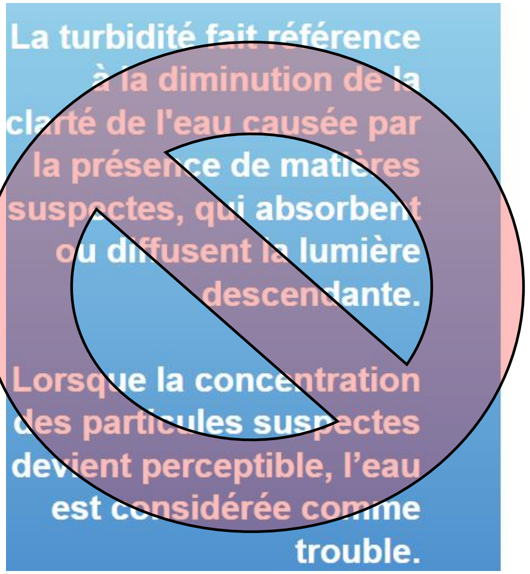
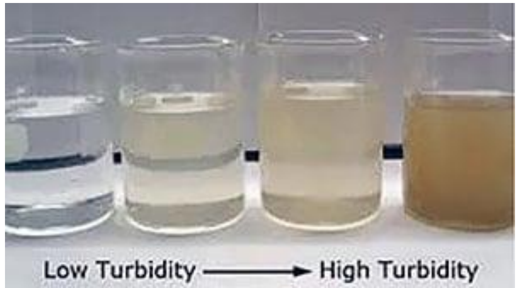


futura-sciences.com

La turbidité est une caractéristique optique de l'eau, à savoir sa capacité à diffuser ou absorber la lumière incidente. La turbidité est due à la présence dans l'eau de particules en suspension minérales ou organiques, vivantes ou détritiques.

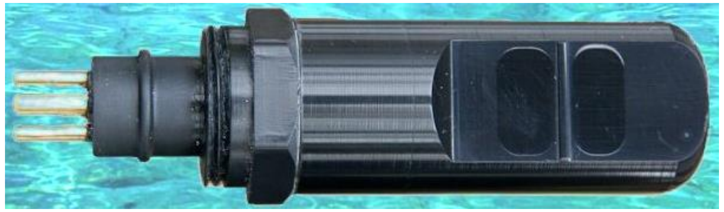


Turbidimetry

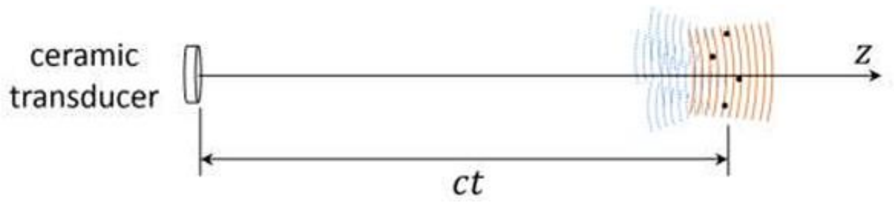
Wave-matter interaction

EM waves → Optic

Mechanical waves → Acoustic



Acoustical turbidimetry



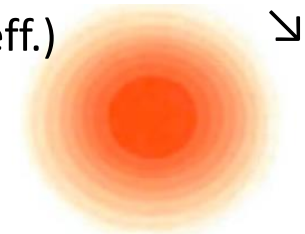
Intensity at a distance r from the source : $I_r = \frac{p_r^2}{\rho c}\ [W.m^{-2}]$

Sonar Equation: SE = SL – 2TL + TS – (NL-DI) - DT

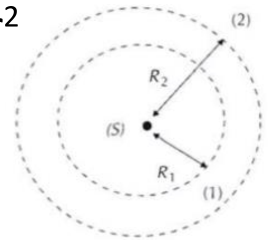
Signal Excess

Source Level $SL = 10.\log_{10}\frac{I}{I_{ref} = 1\mu Pa}$

Transmission Loss $TL = 20.\log_{10} r + ar$ (r : distance, a : absorption coeff.)



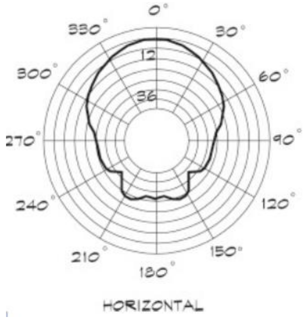
↘1/r²



Target Strenght

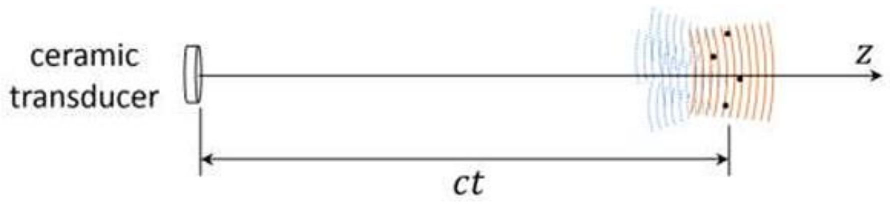
Noise Level $NL = N_0 + 10.\log_{10} w$ (N_0 : local noise, w : bandwith transducer)

Directivity Index $DI = 10.\log_{10} Q$ (Q : directivity factor)



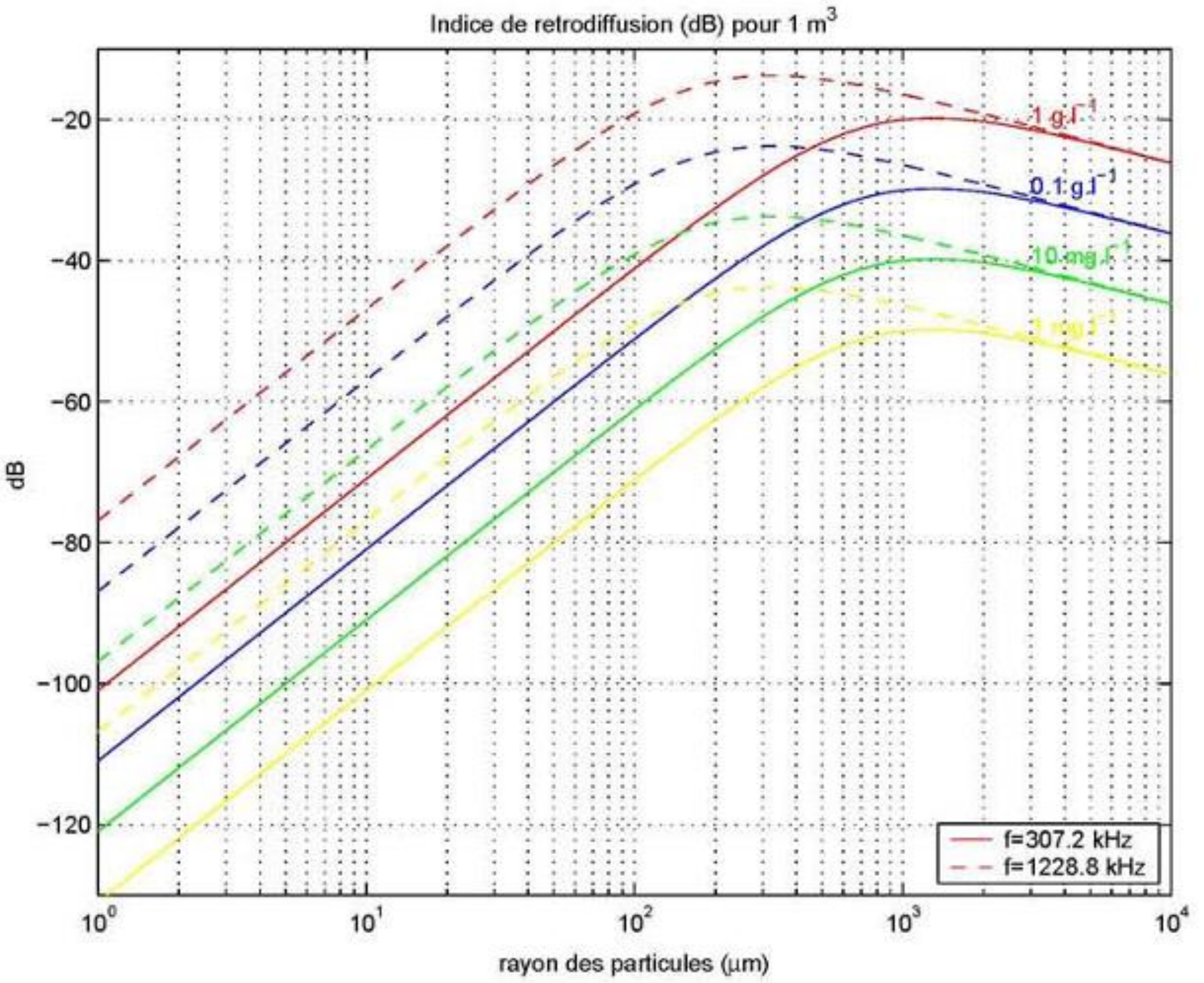
Detection Threshold

Acoustical turbidimetry



Sonar Equation: SE = SL – 2TL + TS – (NL-DI) - DT

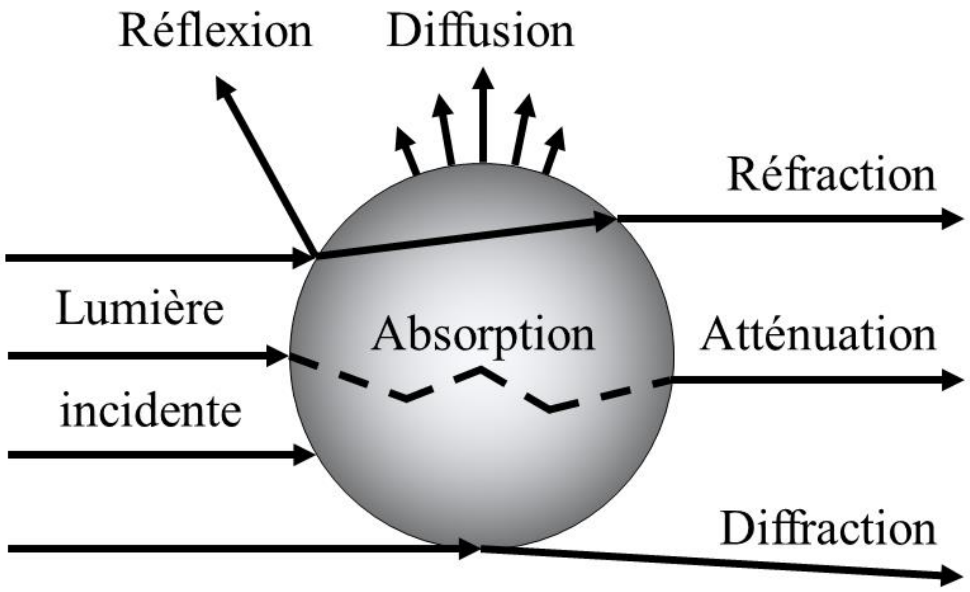
Signal Excess
Source Level
Transmission Loss
Target Strenght
Noise Level
Directivity Index
Detection Threshold



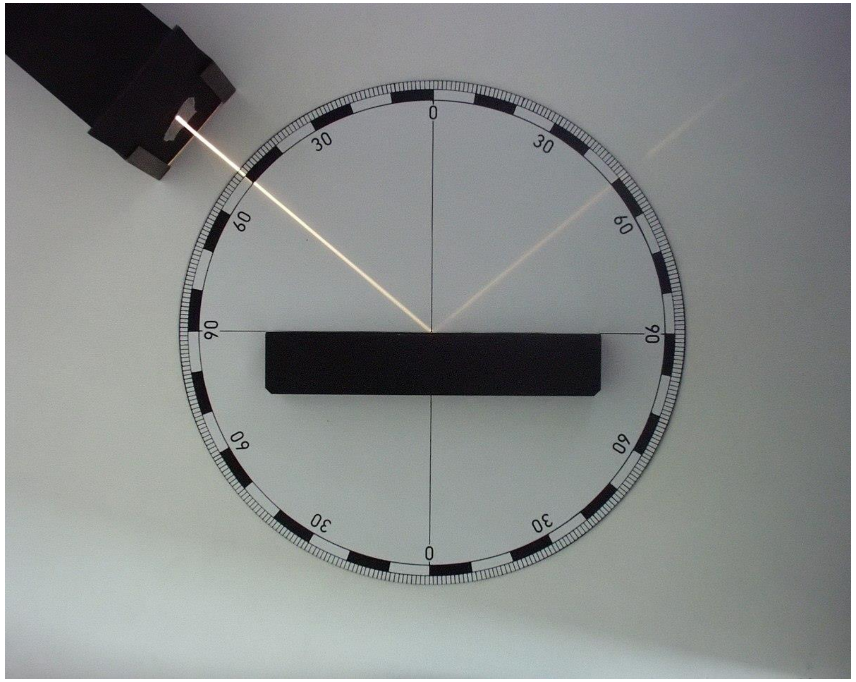
Volumic backscatter index function of particles radius for mass concentration from 1mg/l to 1g/l, for two different frequencies. Mineral particles.
(Tessier, C. 2006)

… but complex (if you want to estimate particle size) :
- total attenuation caused by particles (viscosity absorption + scattering), depending of type : size/density => hypothesis needed to reverse signal
- ideally multi-spectral, or optimize frequency with particle size expected
- SSC integrated on a volume, depending bin size (so freq.)
- Big raw data processing

Optical turbidity



Optical turbidity



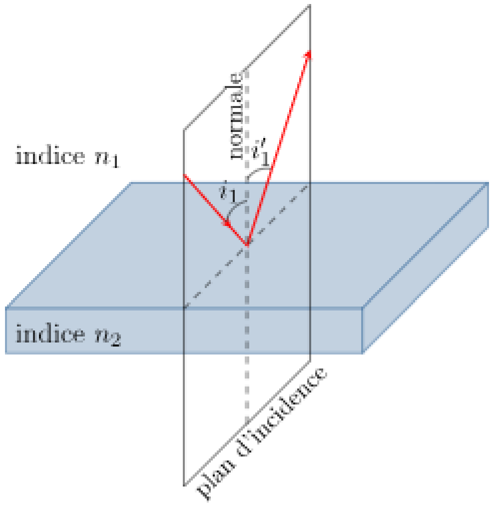
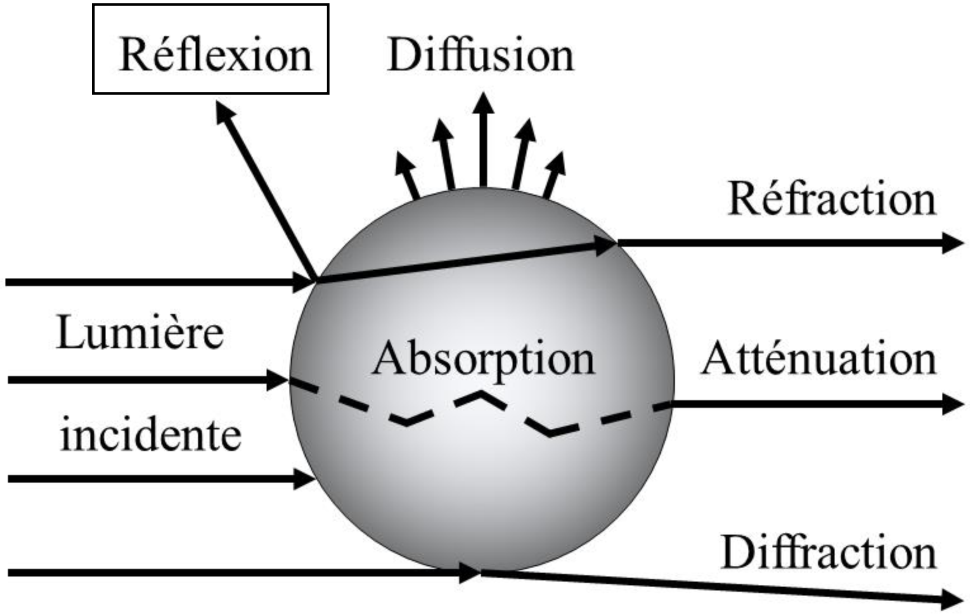


Fig. 4- *Réflexion d'un rayon sur une interface.*

$$i_1 = i'_1$$



Optical turbidity

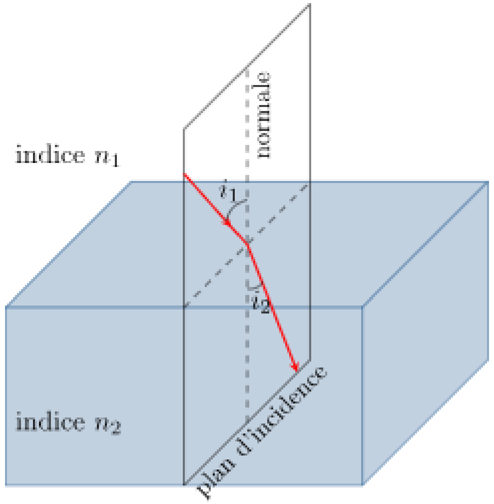
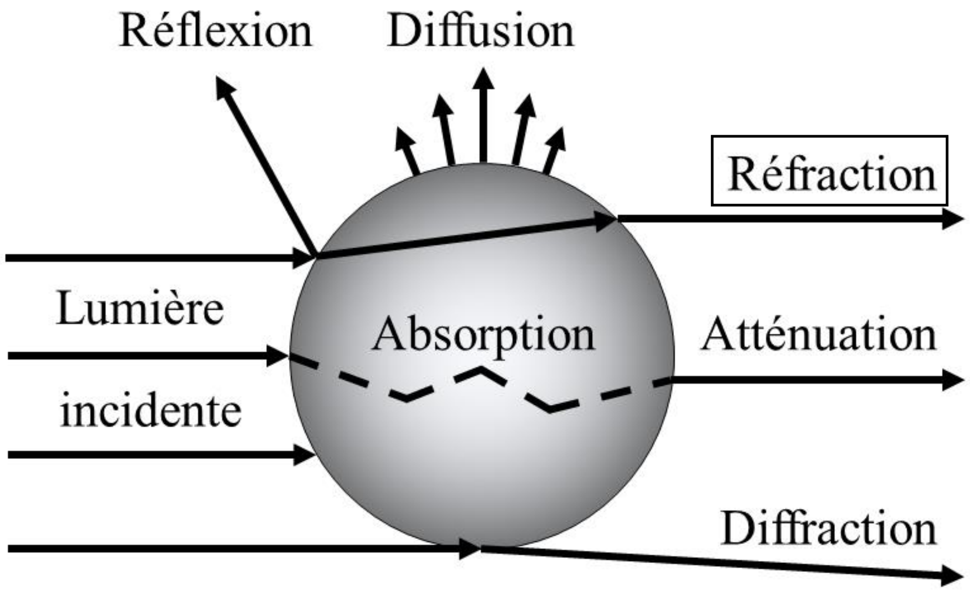


Fig. 5- *Réfraction d'un rayon sur une interface.*



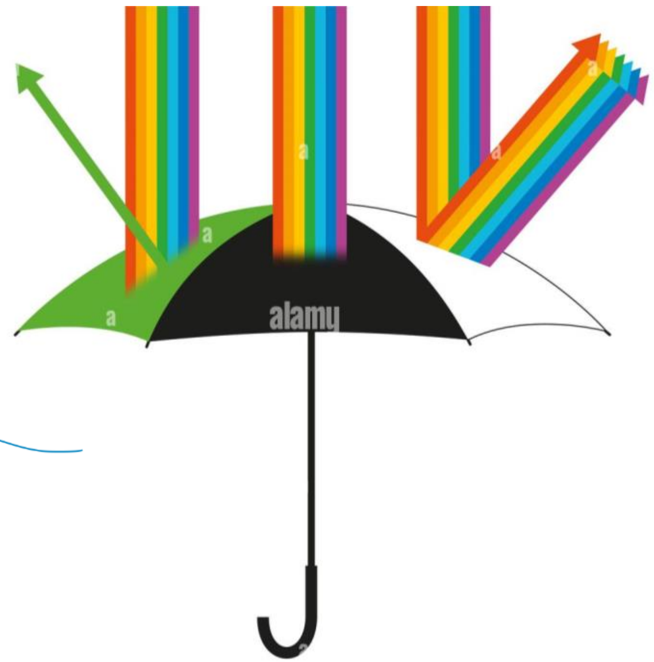
Snell-Descartes :

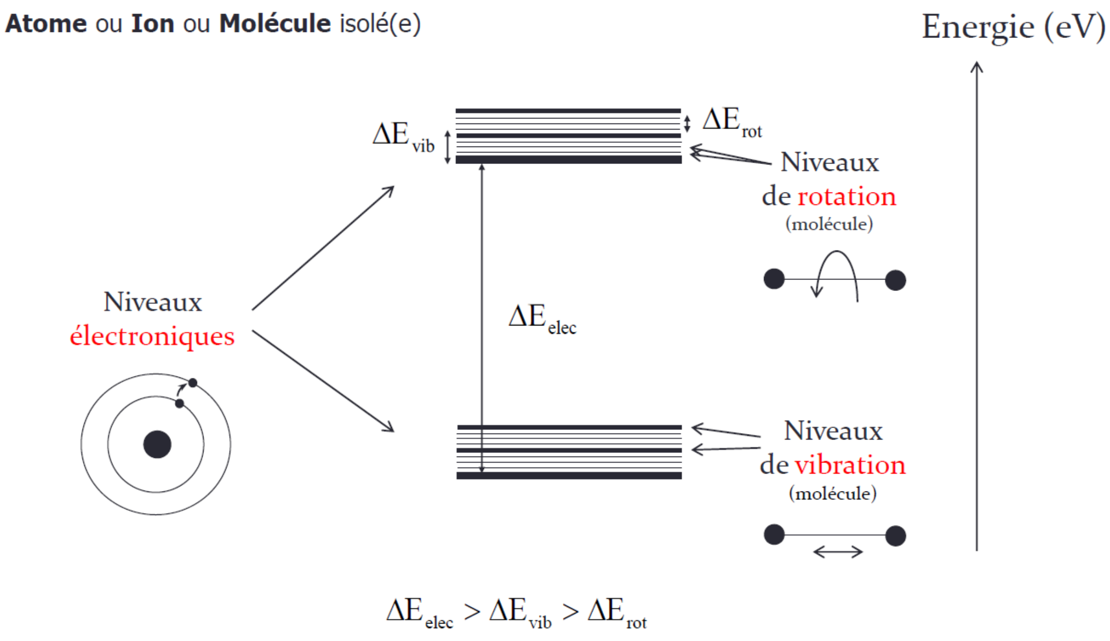
$$n_1 . \sin i_1 = n_2 . \sin i_2$$

Cauchy :

$$n(\lambda) = A + \frac{B}{\lambda^2}$$

Optical turbidity





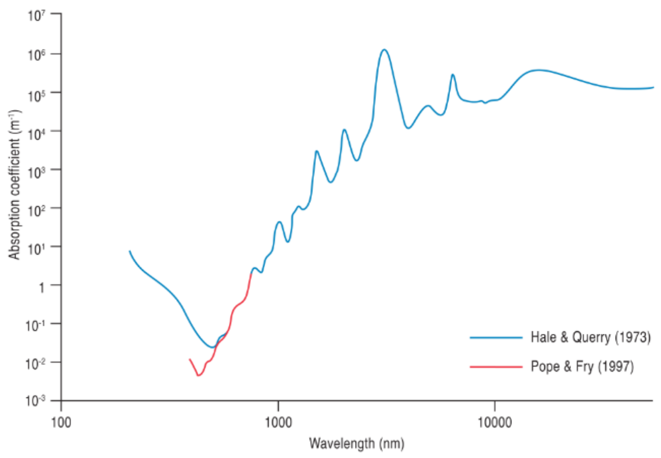
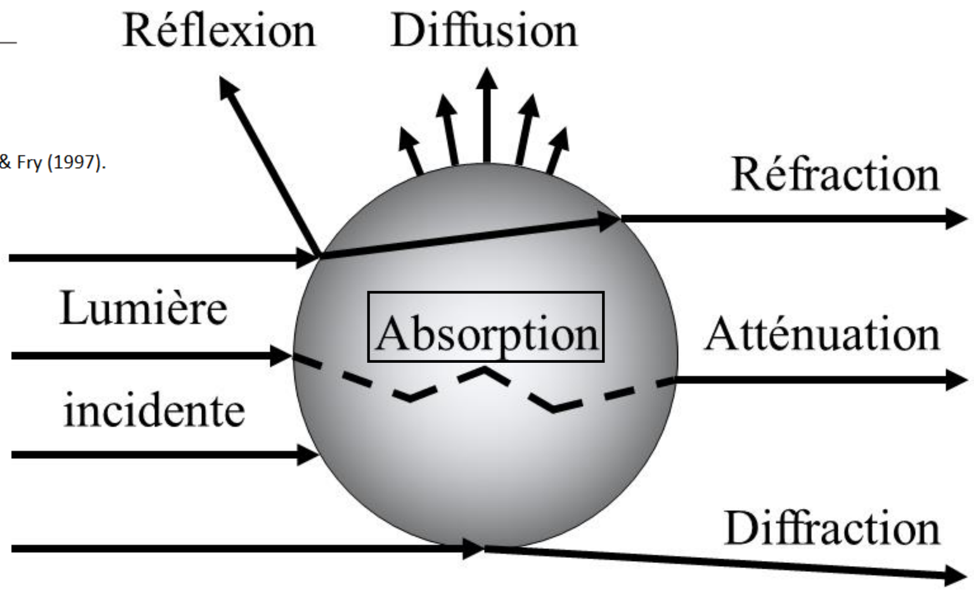
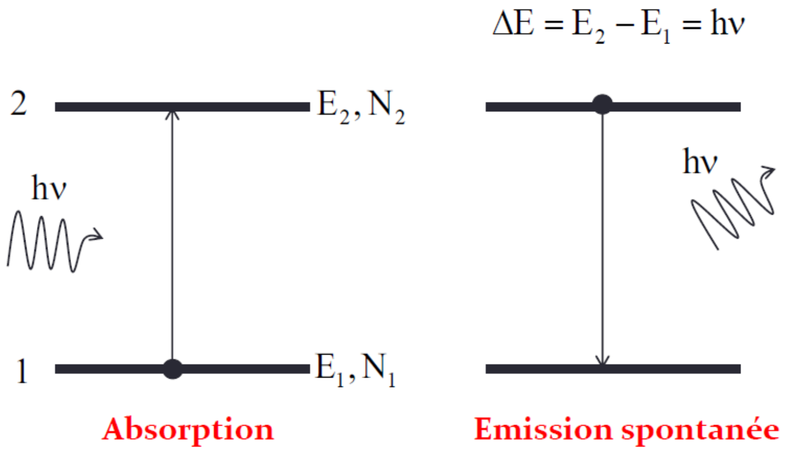
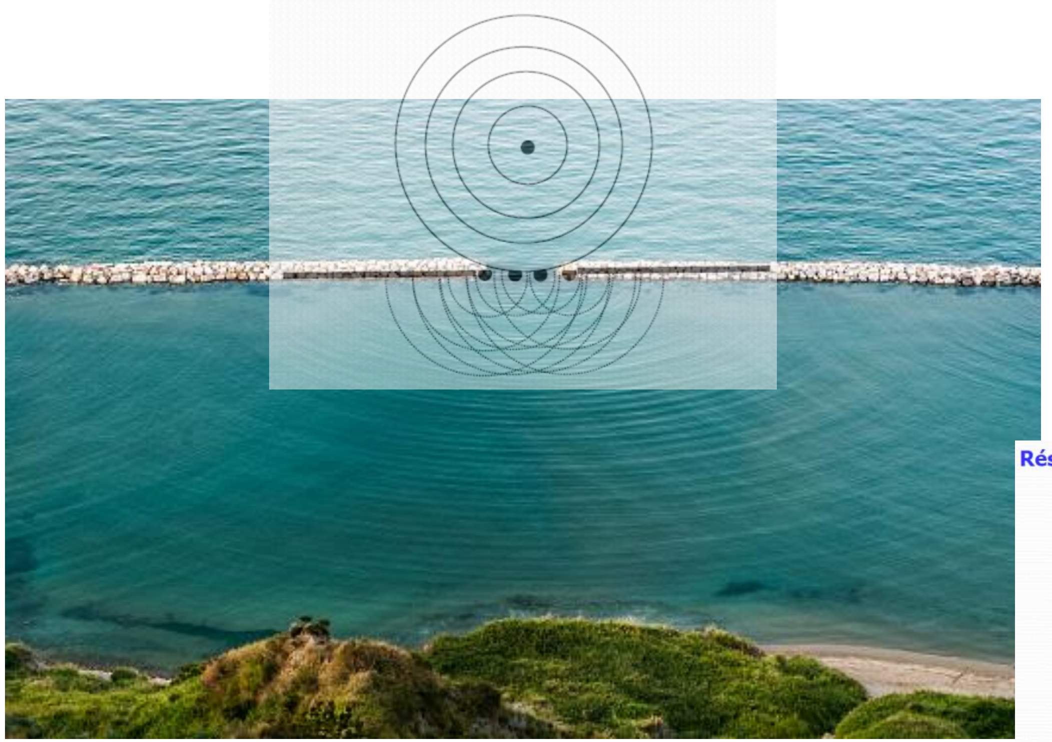


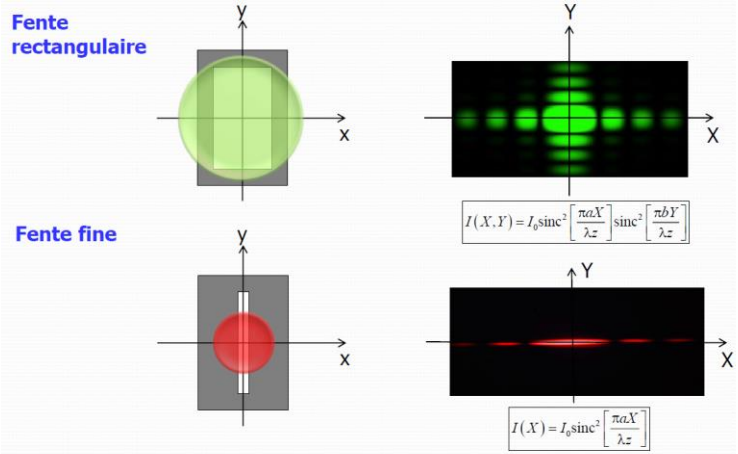
Figure 5. The light absorption spectrum of water. After Hale & Querry (1973) and Pope & Fry (1997).

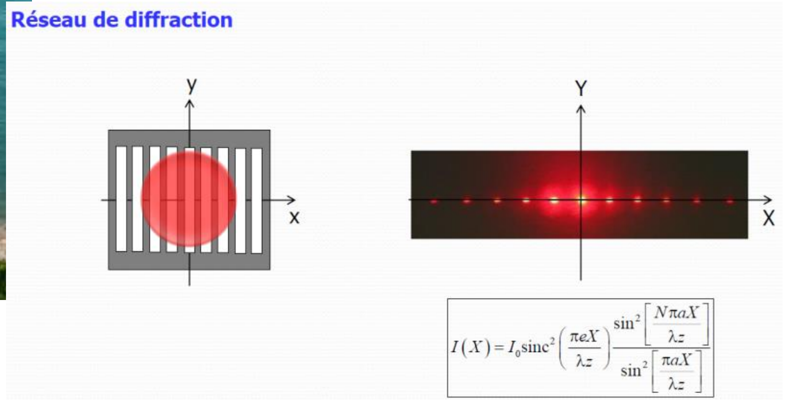


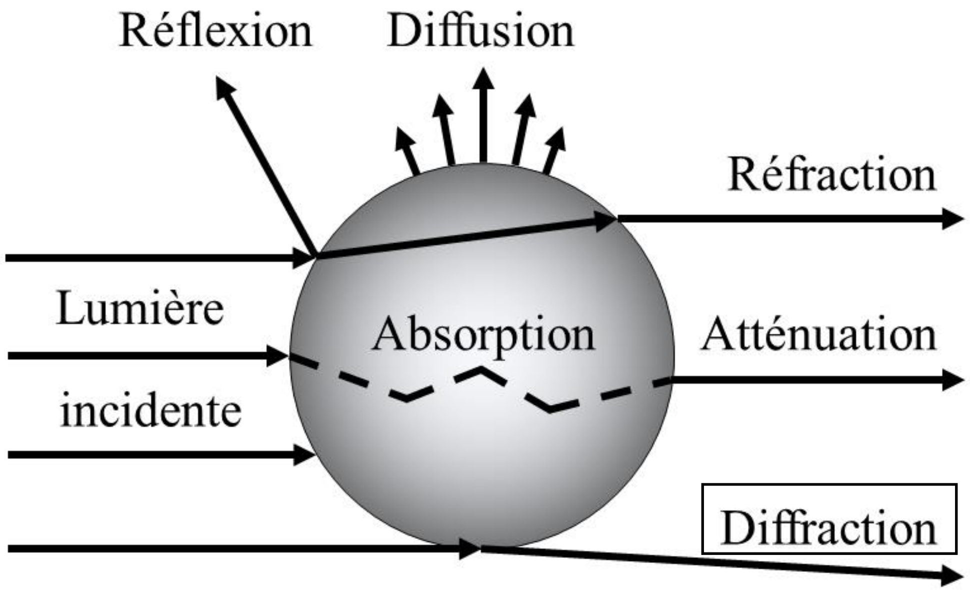


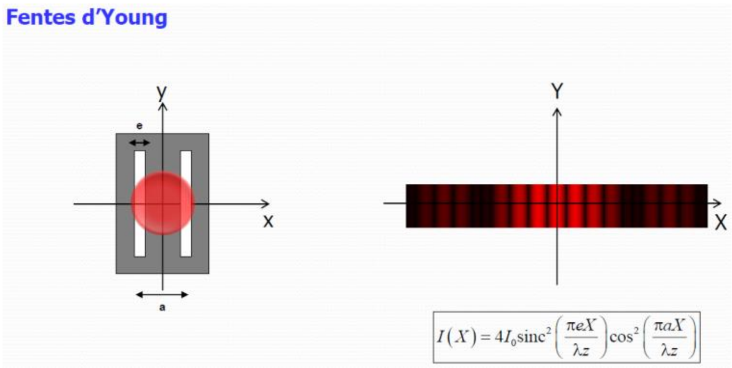
Optical turbidity

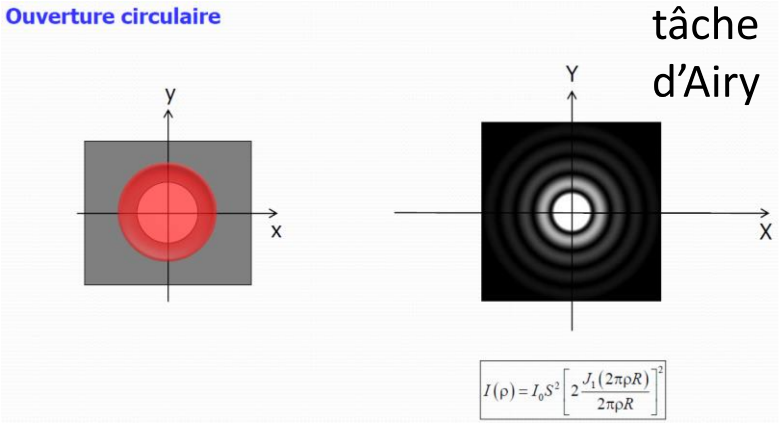




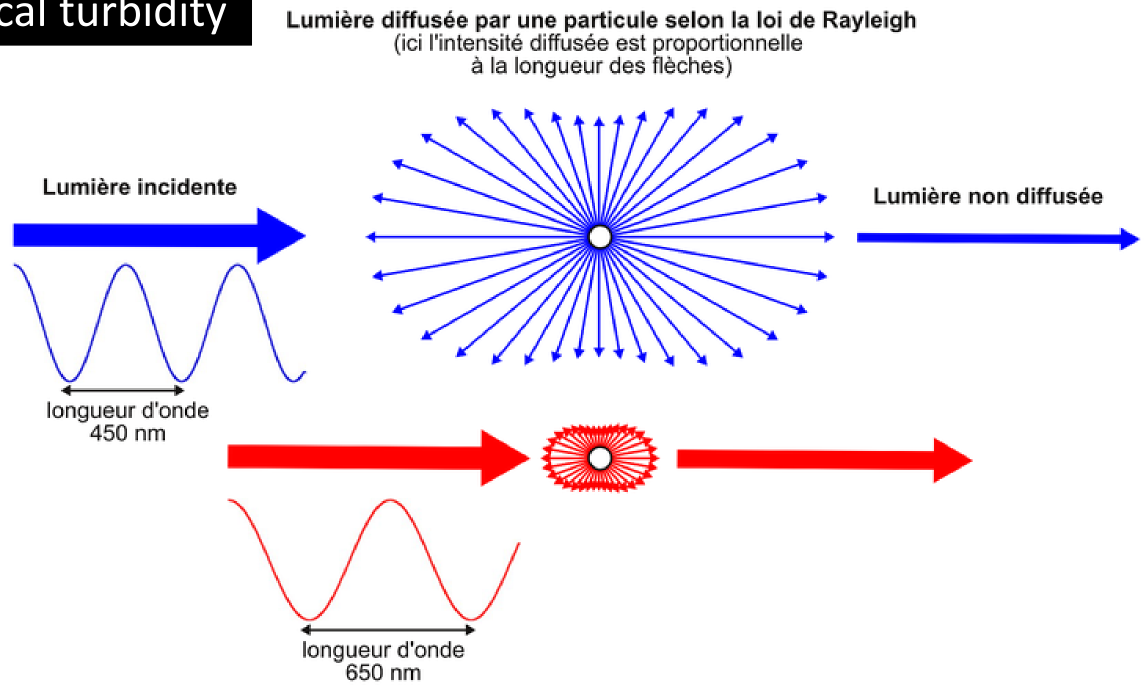


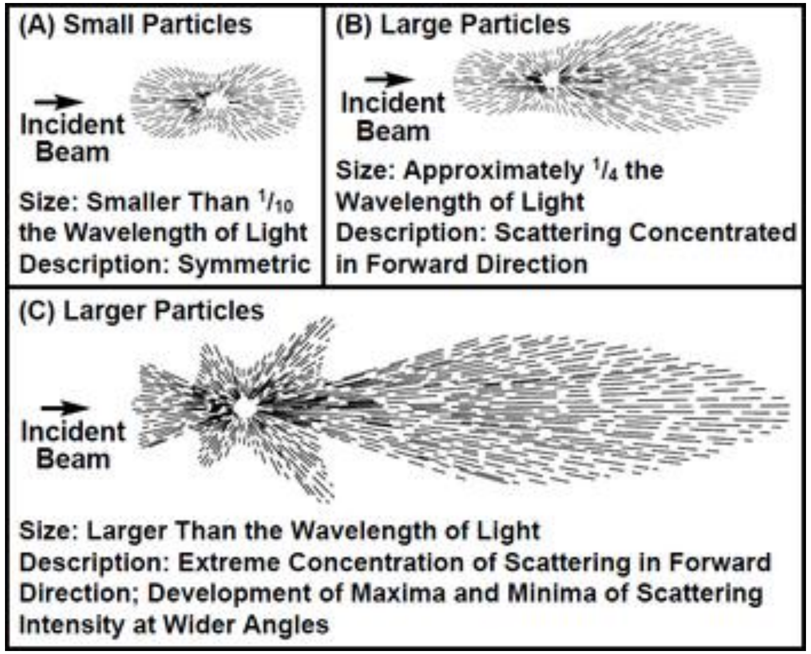


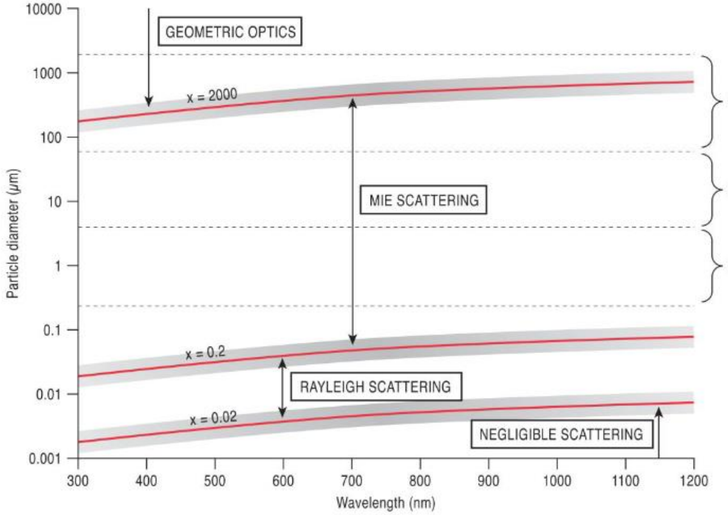


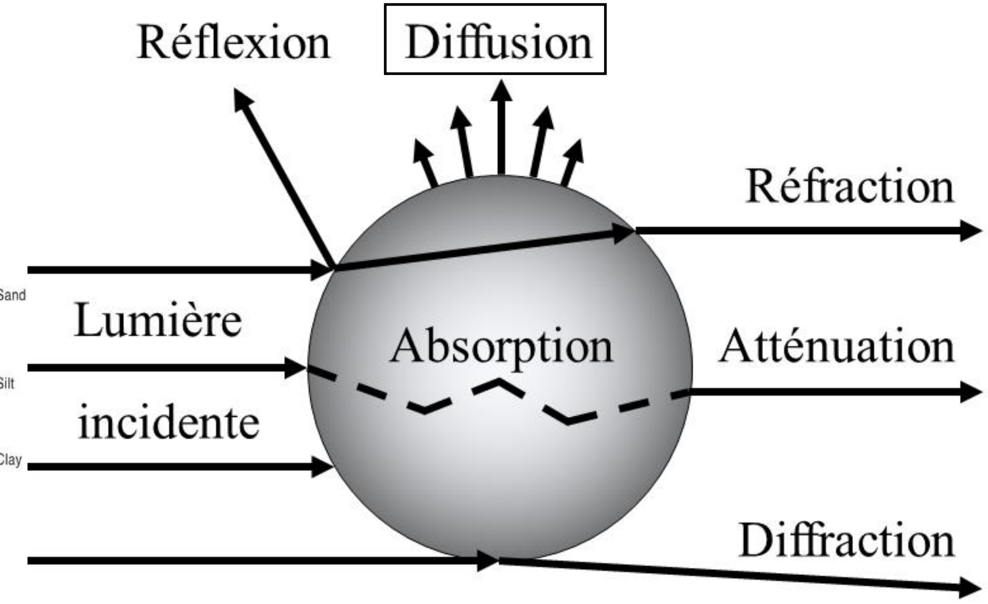


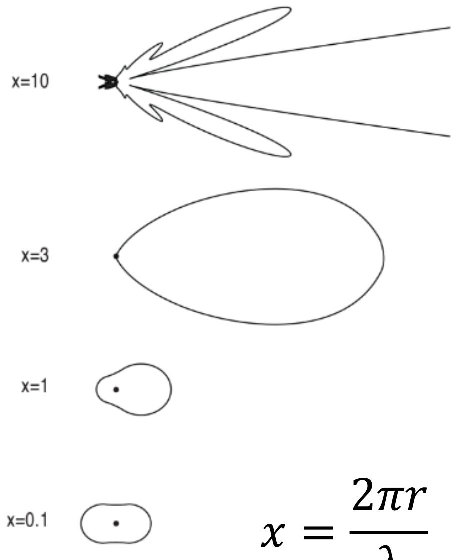
Optical turbidity







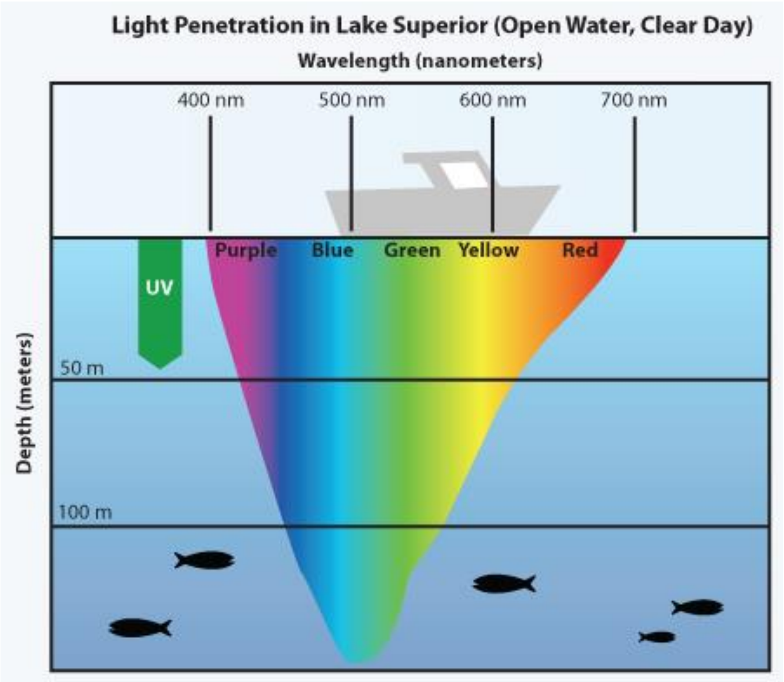


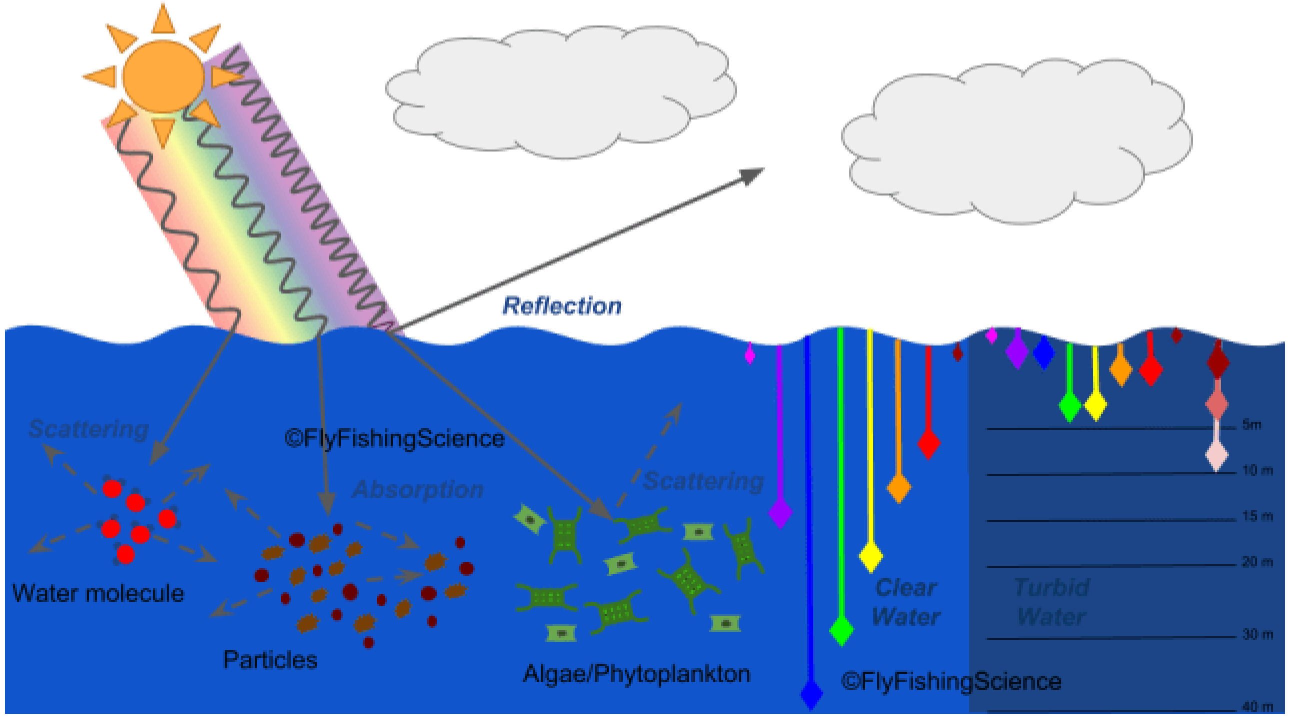


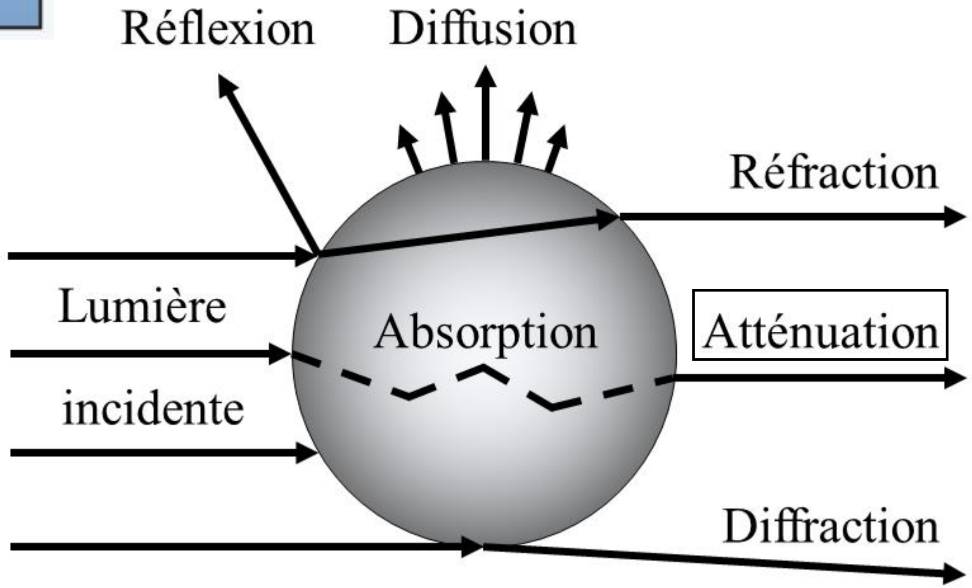
$$x = \frac{2\pi r}{\lambda}$$

Figure 2. Scattering phase functions derived from Mie theory, with light incident from the left of the diagrams. Forward scattering becomes more pronounced as x increases.

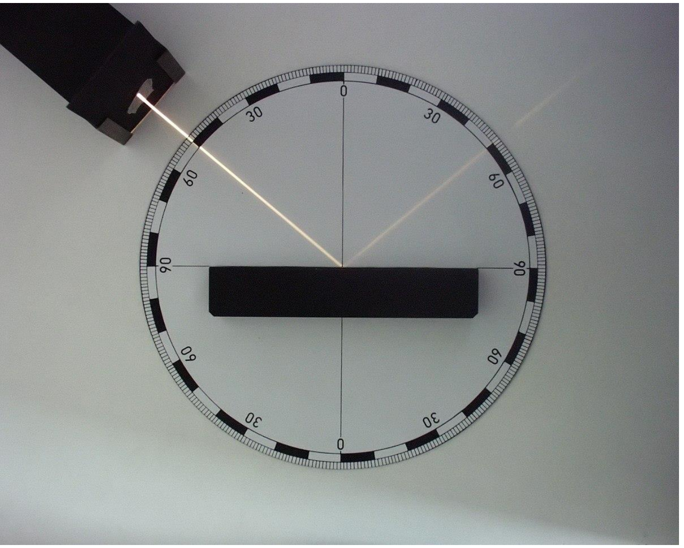
Optical turbidity

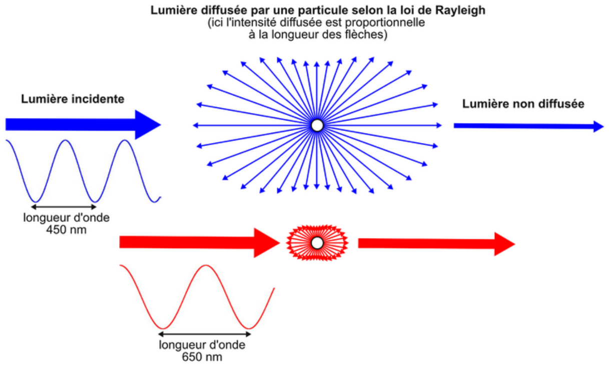


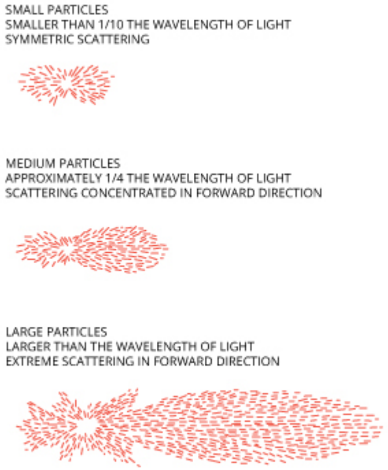


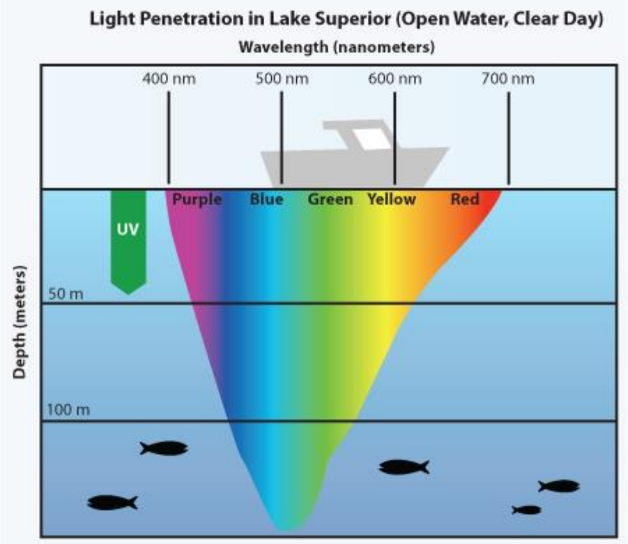


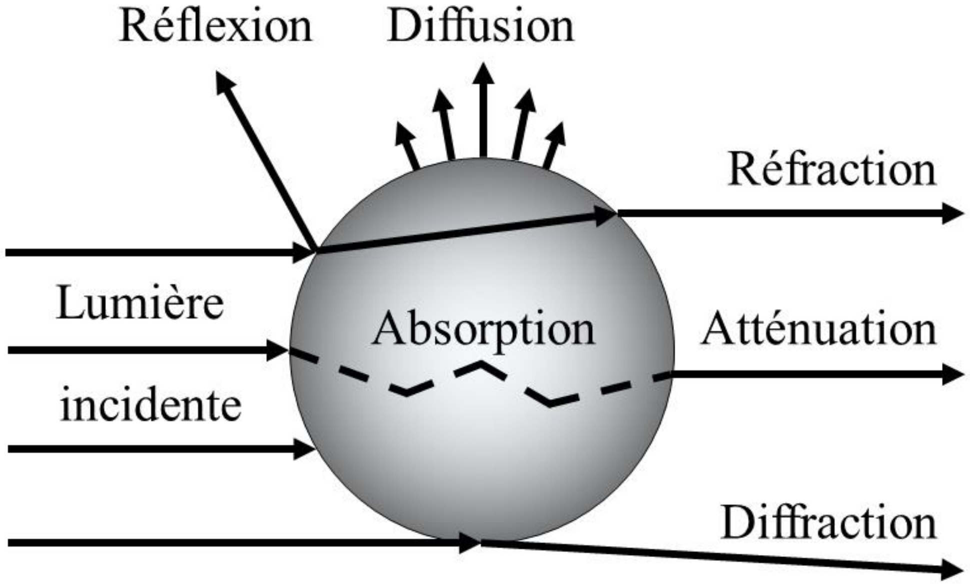
Optical turbidity



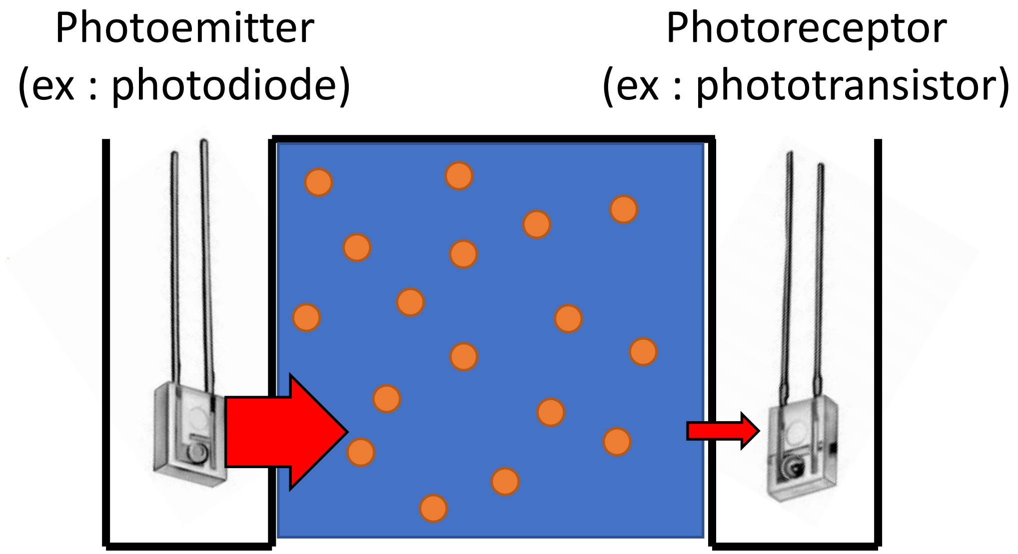


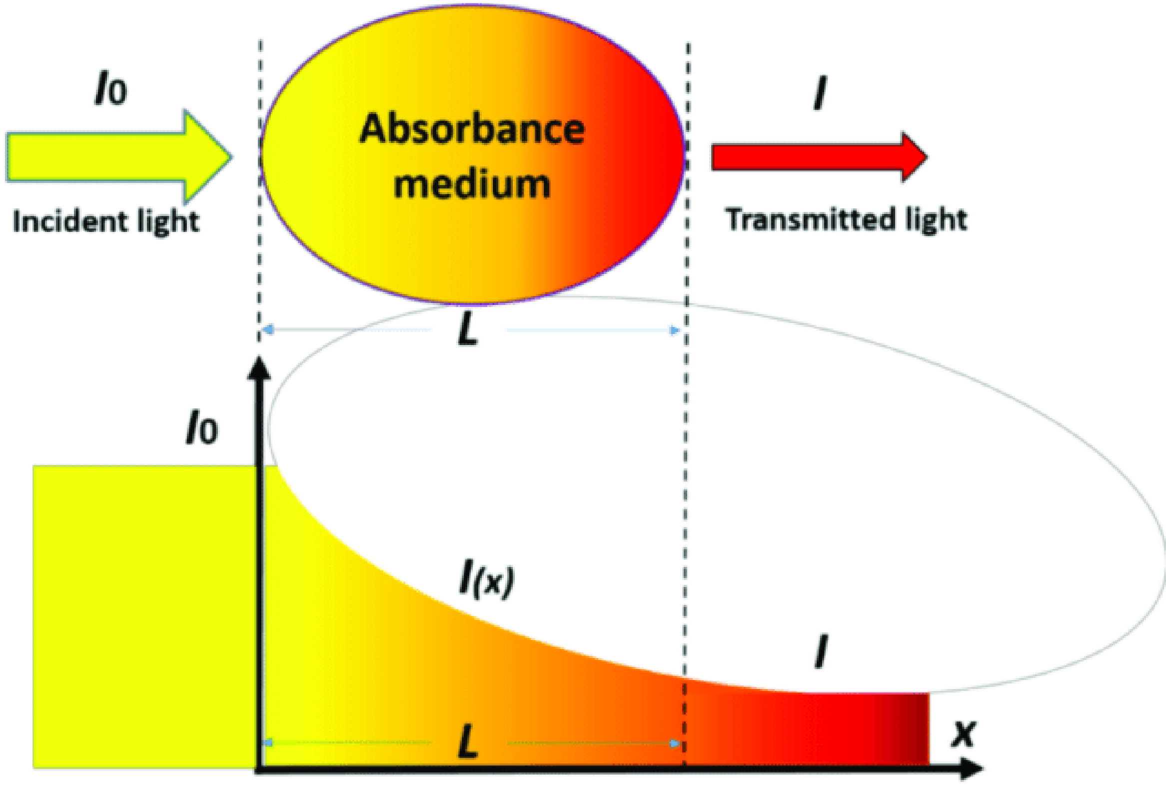






Transmissiometry

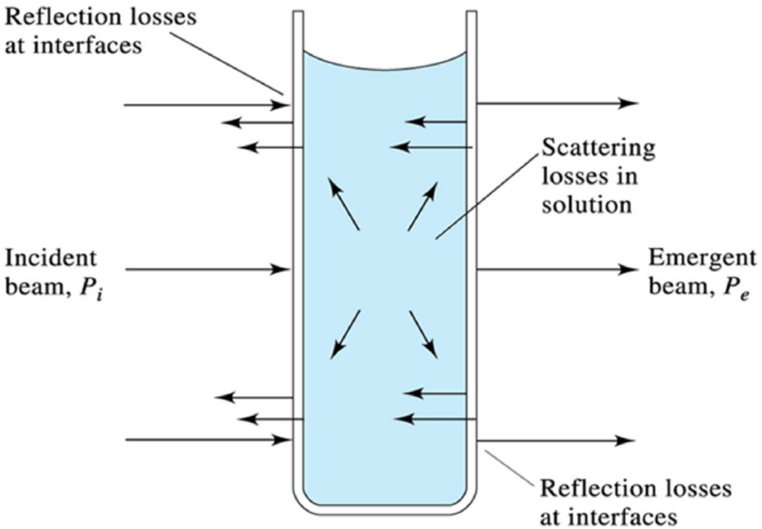




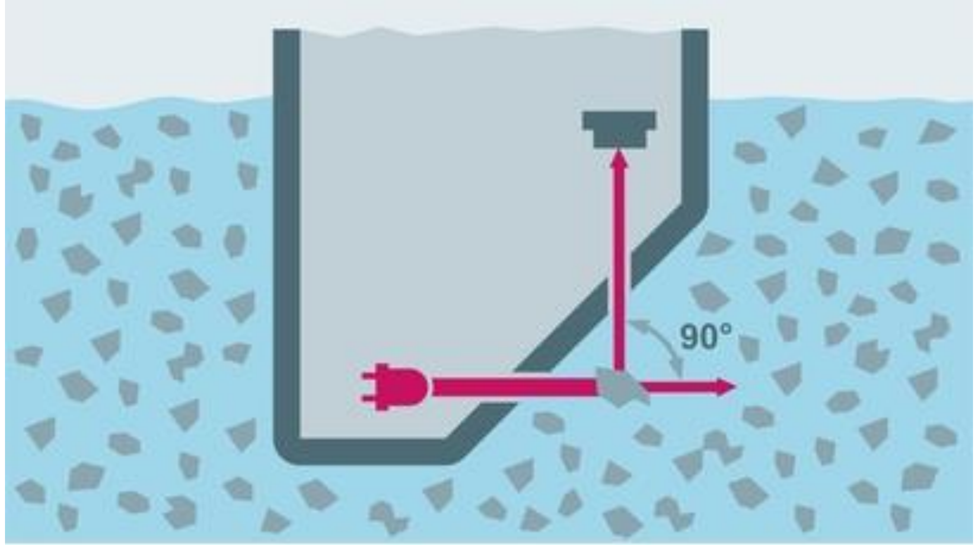
Beer-Lambert

$$\frac{I}{I_0} = e^{-\mu_{att} \cdot L}$$

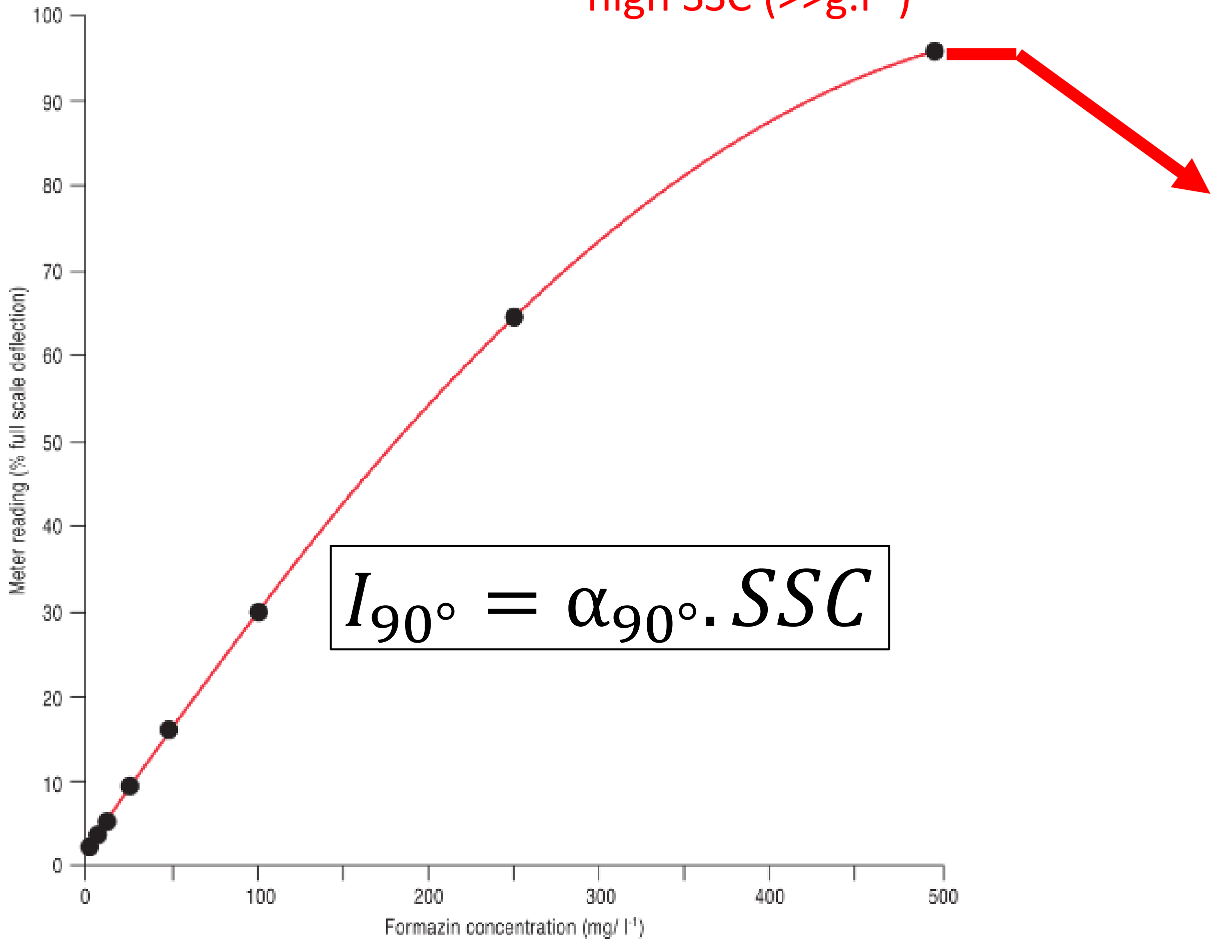
$$\mu_{att} \propto C_{MES}$$



Nephelometry



reach a max., then decrease @ high SSC (>>g.l^{-1})



$$I_{90°} = \alpha_{90°}.SSC$$

Figure 8. Laboratory calibration of a turbidity meter with Formazin standards. Meter readings of the neutral density filters used in the field are shown also (Finlayson 1985).

Nephelometry

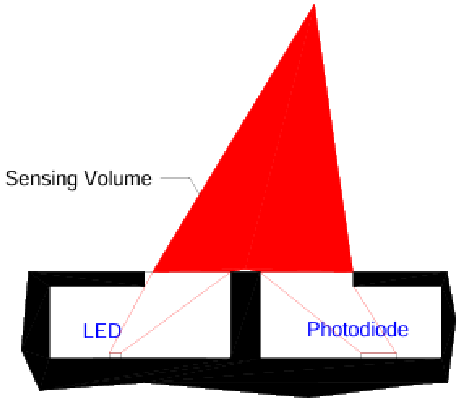
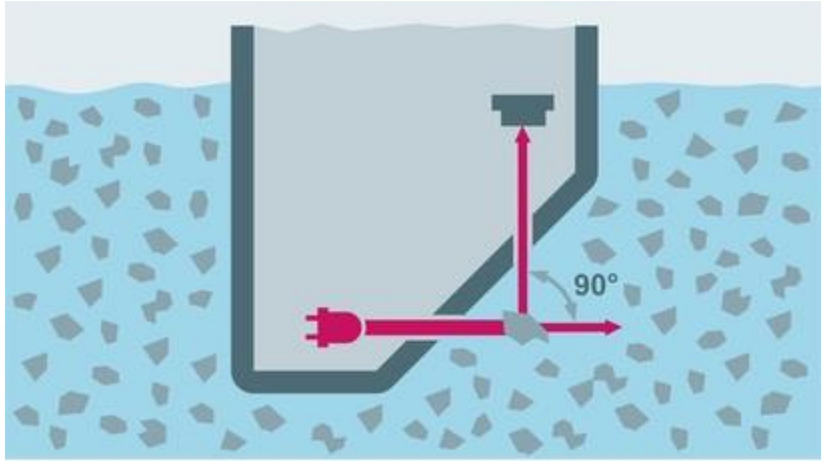
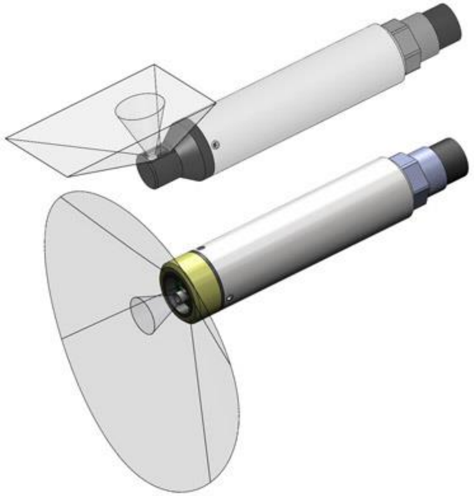


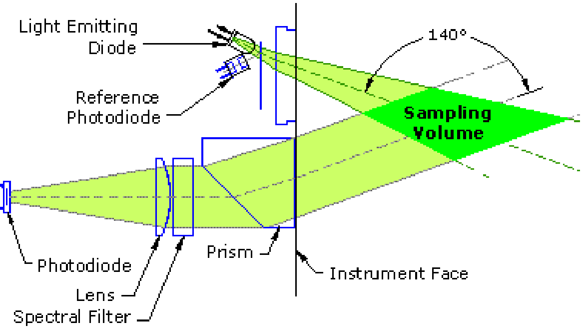
Figure 2. Diagram of Seapoint Turbidity Meter Optics

Seapoint (STM-S)

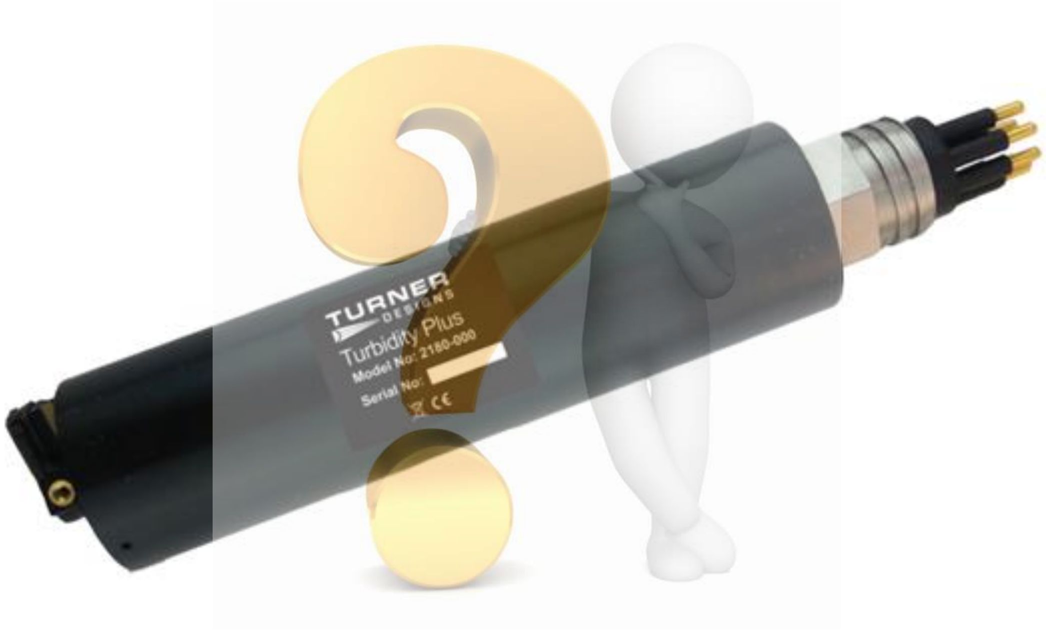




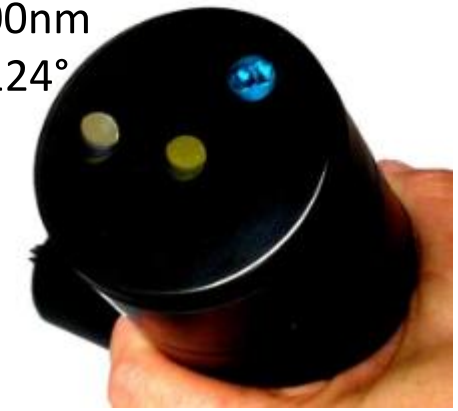
Campbell Sci.
(OBS-3+ & OBS300)



HOBI Labs
(HydroScat)



λ=700nm
θ=124°



WETLabs
(ECO NTU & BB)

Optical fiber

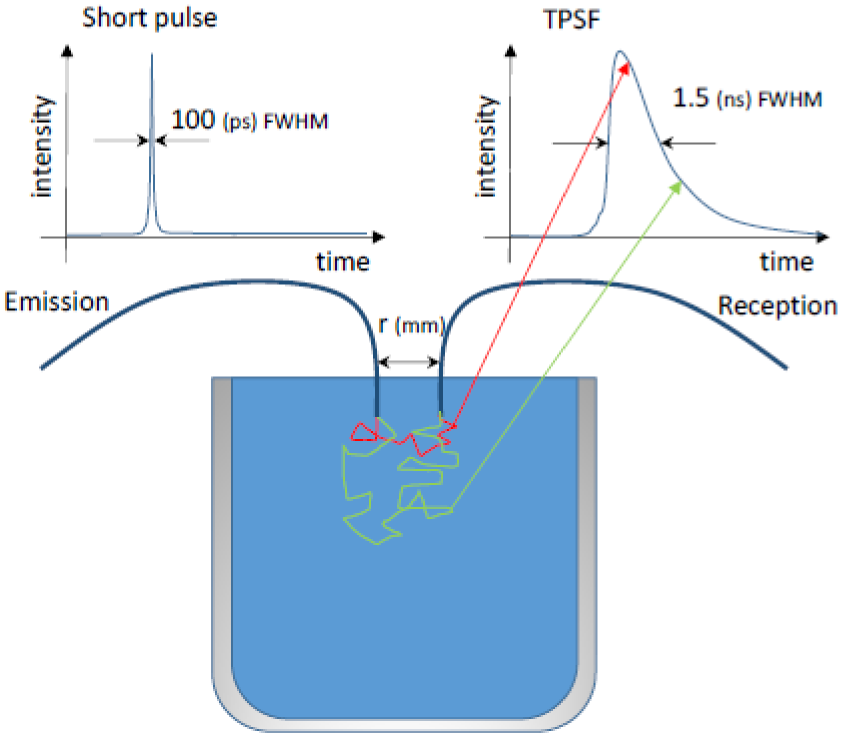


Figure 2. Principle of Time Resolved Optical Turbidity (TROT).

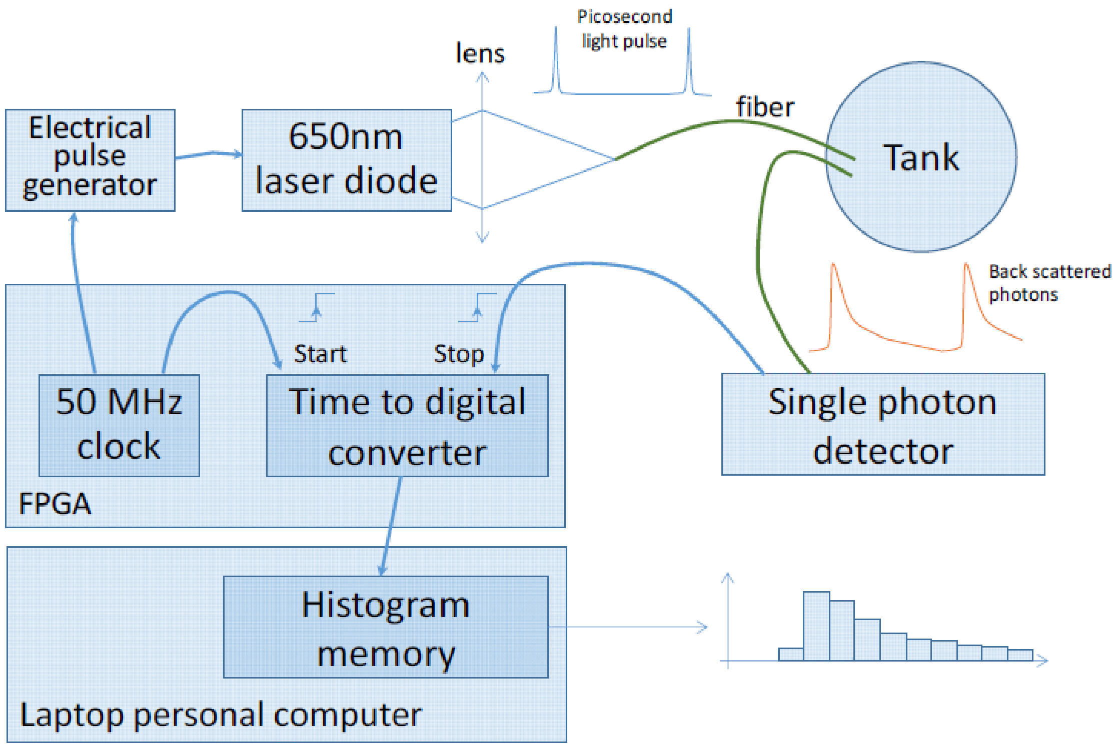
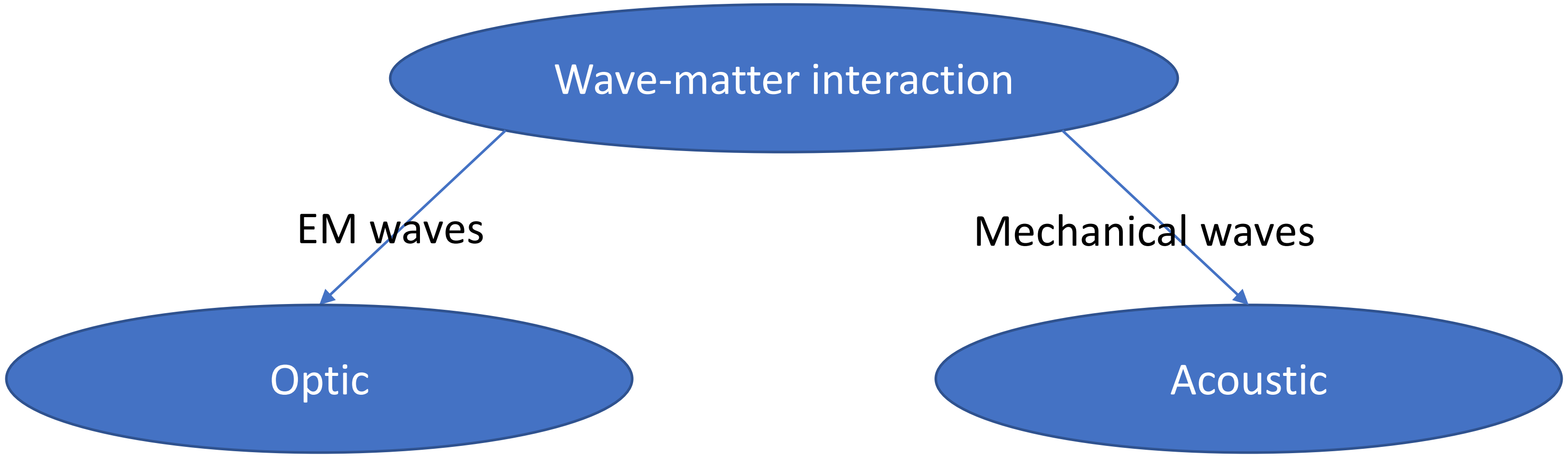


Figure 3. Schematic set-up of TROT.

Pallarès, Anne & Schmitt, P. & Uhring, Wilfried. (2021). Comparison of Time Resolved Optical Turbidity Measurements for Water Monitoring to Standard Real-Time Techniques. Sensors. 21. 10.3390/s21093136.

Turbidimetry

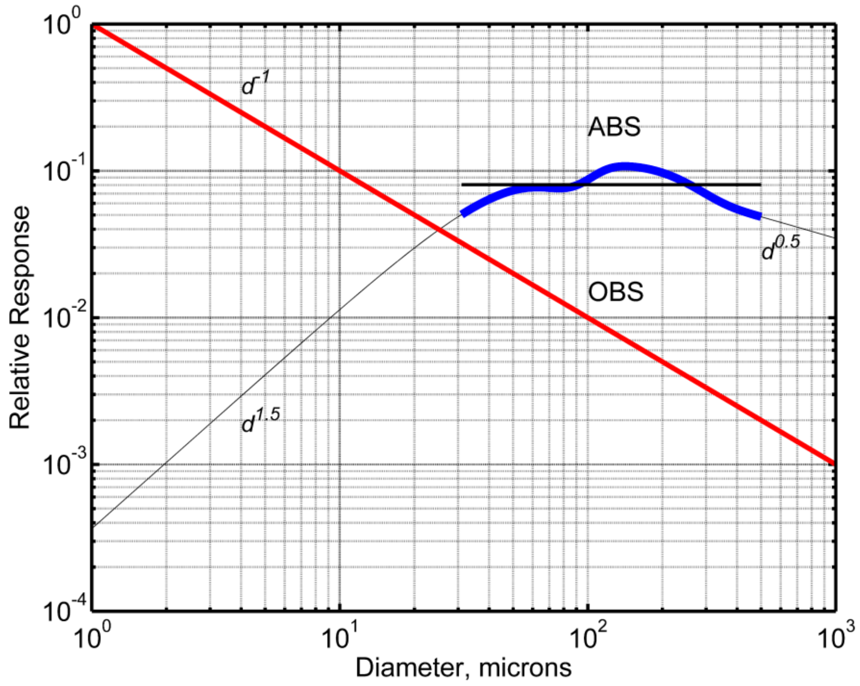


+ :

Sensitivity to small particles (mud and smaller)

- :

Less sensitive to bigger particles (sand and higher)
Bio-fouling impact
No linearity @ high SSC



+ :

Sensitivity to big particles (sand and more)
No bio-fouling impact

- :

Less sensitive to smaller particles (mud and less)
High electricity consumption
Data processing heavy
Only one ABS sensor manufactured (dark box)

Methods / Units

NF EN ISO 7027-1:2016

Nephelometry
(diffusion @90°)

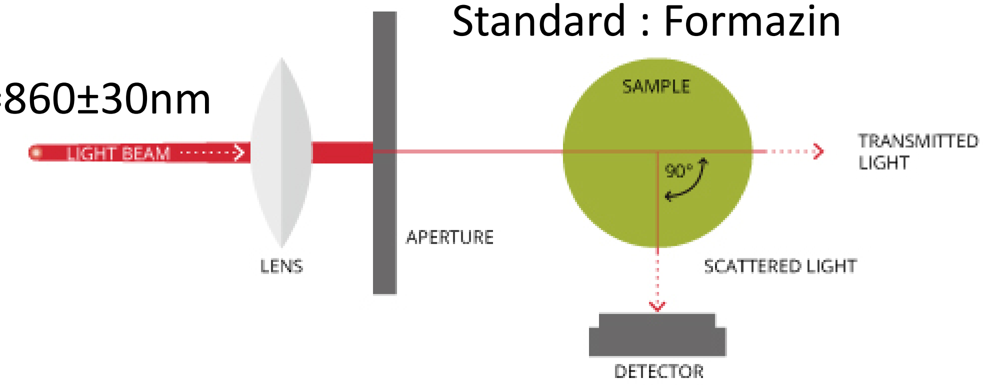
Unit NTU
Range [0;400]NTU or +
NTU=FNU for formazin

Turbidimetry
(attenuation @180°)

Unit FAU
Range [40;4000]FAU

Standard : Formazin

λ=860±30nm



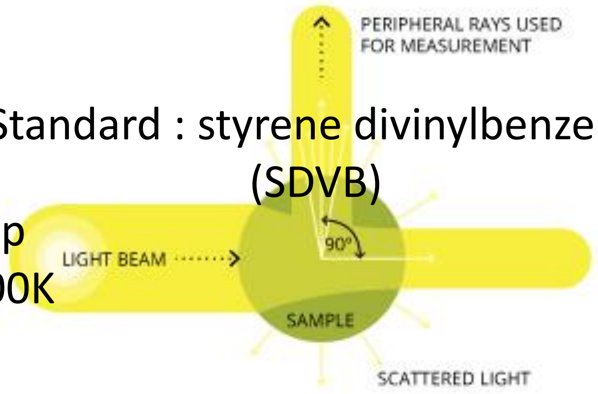
United States Environnemental Protection Agency (USEPA)

8 approved methods :
USEPA Method 180.1
Standard Method 2130GB
Great Lakes Instrument Method 2 (GLI 2)
HACH Method 10133
Mitchell Methods M5271 & M5331
Orion AQ4500
AMI Turbiwell

λ=[400;600]nm

Standard : styrene divinylbenzene (SDVB)

Tungsten lamp
color 2200-3000K



Methods / Units

NF EN ISO 7027-1:2016

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Turbidimetry (attenuation @180°)

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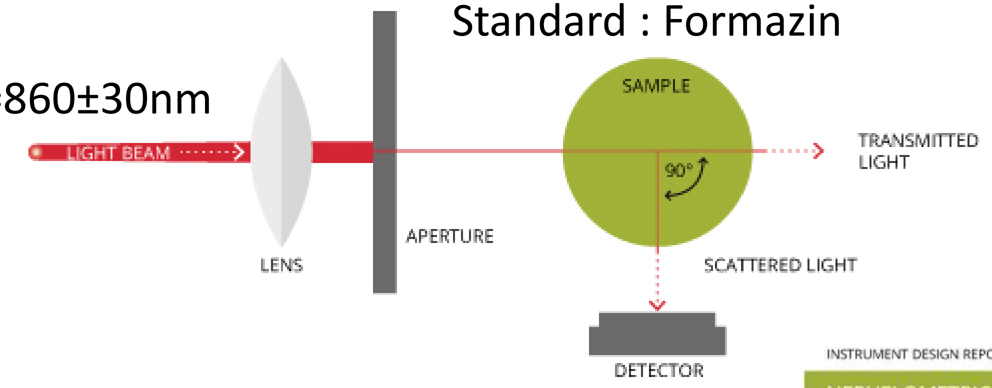

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λ=[400;600]nm

Standard : styrene divinylbenzene (SDVB)

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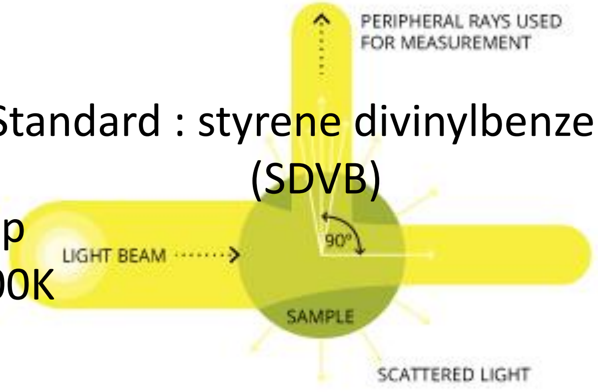


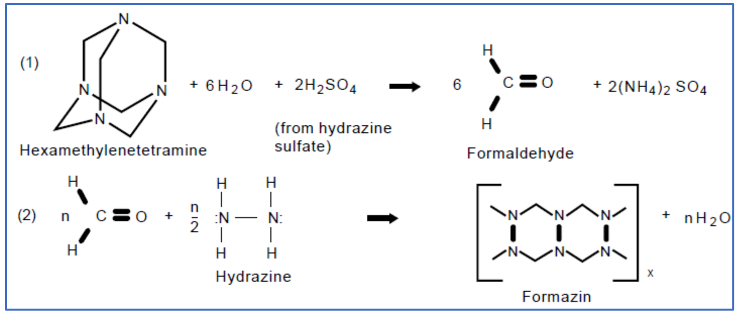
INSTRUMENT DESIGN REPORTING	UNIT
NEPHELOMETRIC NON-RATIO TURBIDIMETERS	NTU
RATIO WHITE LIGHT TURBIDIMETERS	NTRU
NEPHELOMETRIC, NEAR-IR TURBIDIMETERS, NON-RATIOMETRIC	FNU
NEPHELOMETRIC, NEAR-IR TURBIDIMETERS, RATIO METRIC	FNRU
SURFACE SCATTER TURBIDIMETERS	SSU
NEAR-IR OR MONOCHROME LIGHT BACK SCATTER UNIT	FBU
BACKSCATTER UNIT	BU
NEAR-IR OR MONOCHROME LIGHT ATTENUATION UNIT	FAU
LIGHT ATTENUATION UNIT	AU
NEPHELOMETRIC TURBIDITY MULTIBEAM UNIT	NTMU
NEPHELOMETRIC LASER-DIODE TURBIDIMETERS	mNTU

FNU : Formazin Nephelometric Unit,
ref. ISO 7027, LED 860nm
(photodetector @ 90°)

NTU : Nephelometric Turbidity Unit
ref. USEPA 180., tungsten white light
(photodector 400-600nm @ 90°)

Formazin (C2H4N2) = Hexamethylenetetramine + Hydrazine Sulfate



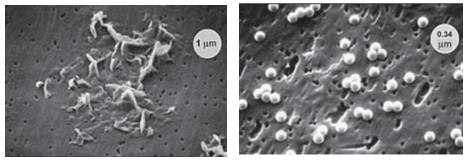


Avantages :

- High reflectivity
- Low absorption
- Repeatble
- Density ~ Eau
- Approved by US EPA, ISO
- Stable over time (@4000 NTU)

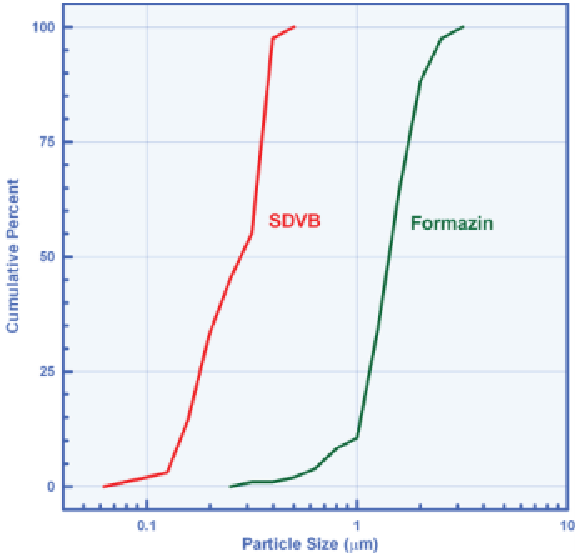
Inconvénients :

- Unstable on high dilutions
- Lab reagents dangerous for health and environment

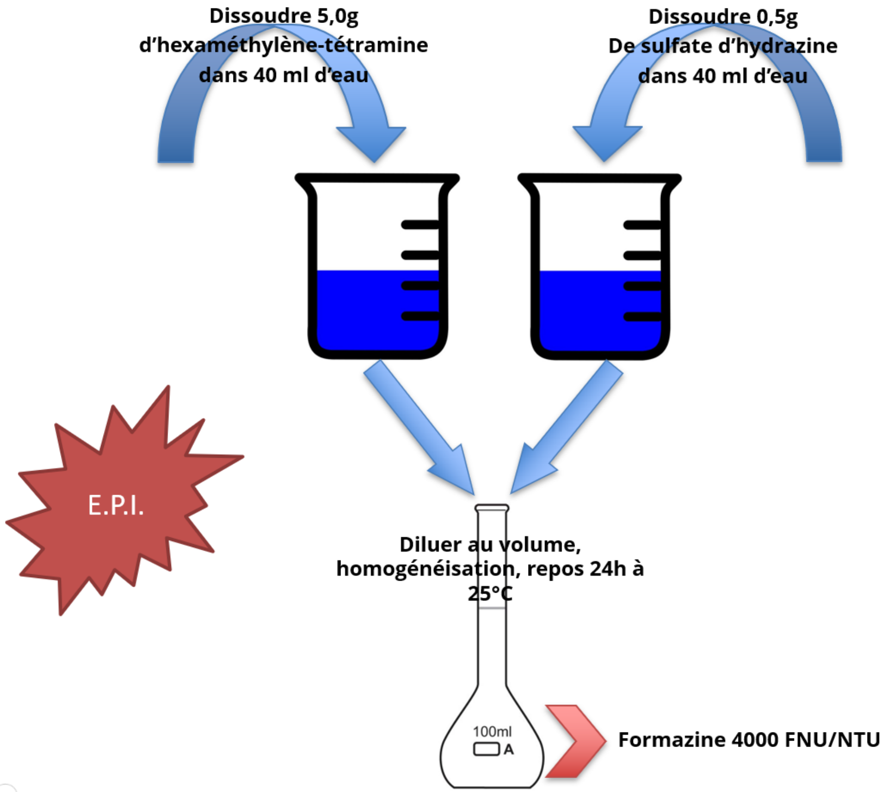


FORMAZIN
D_{50} = 1,5 µm ± 0,6 µm

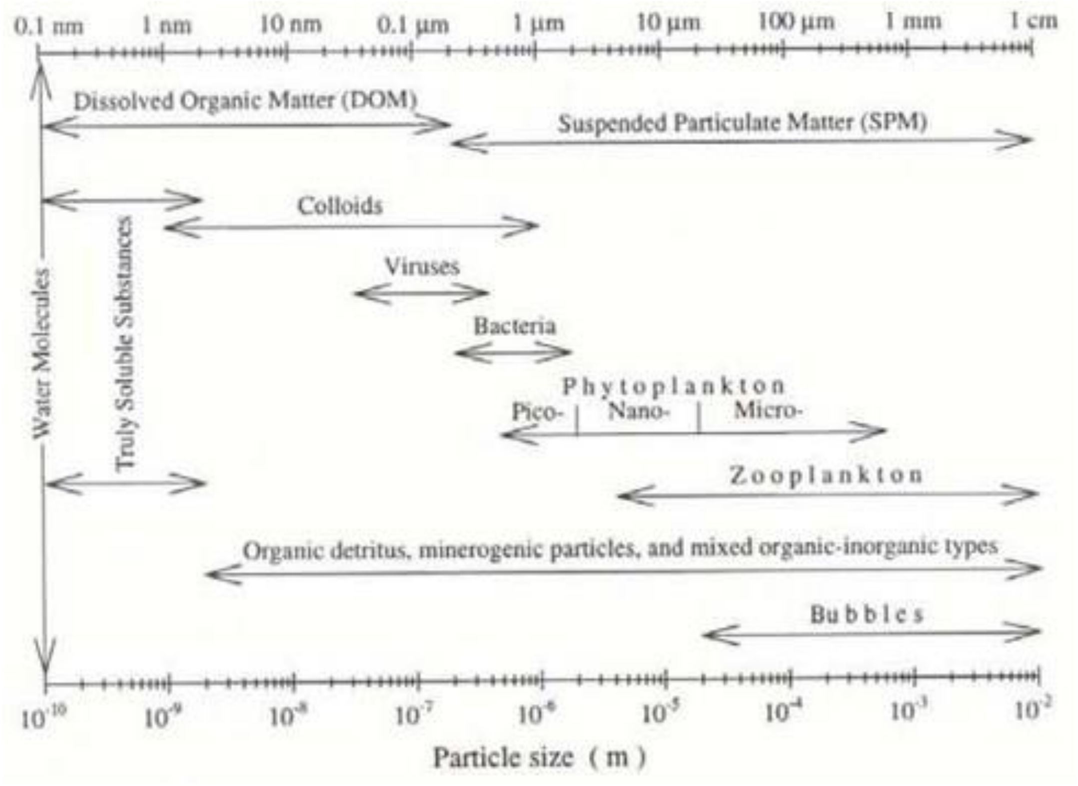
AMCO Clear
(SDVB)



Turbidité [FNU]	Storage Time
400 to 4000	6 months
40 to 400	4 weeks
0 to 40	1 day



SSC



Main components of sea water (Stramski et al. 2004)

... but turbidity depend of :

- measurement method
- particles size/shape

Seasonal hydrodynamic variability

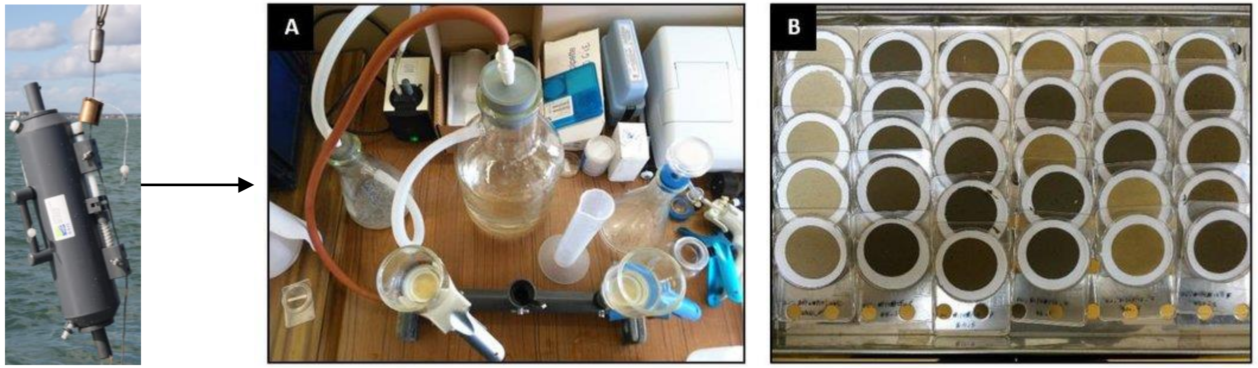
Be careful when compare different sensors/location!!!

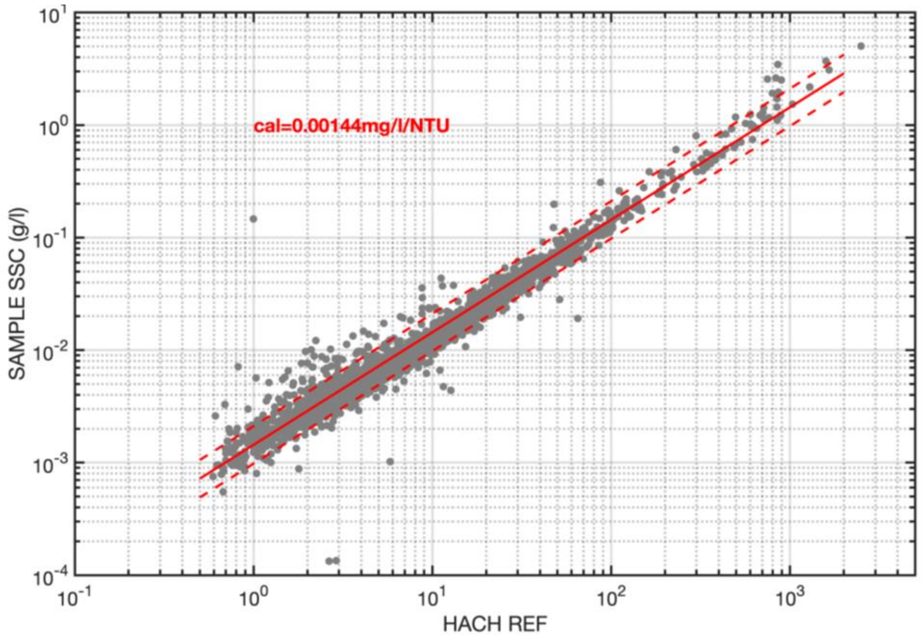
Add particle sizer

Add multi-spectral optic/acoustic sensors

Turbidity measurement
Volts, Counts, NTU, dB, ...

Calibration
Turbidity / SSC

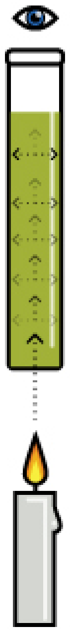




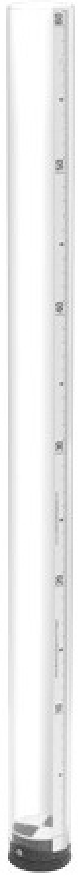
Calibration of a HACH lab turbimeter reference in mass concentration (Verney et al. 2022)

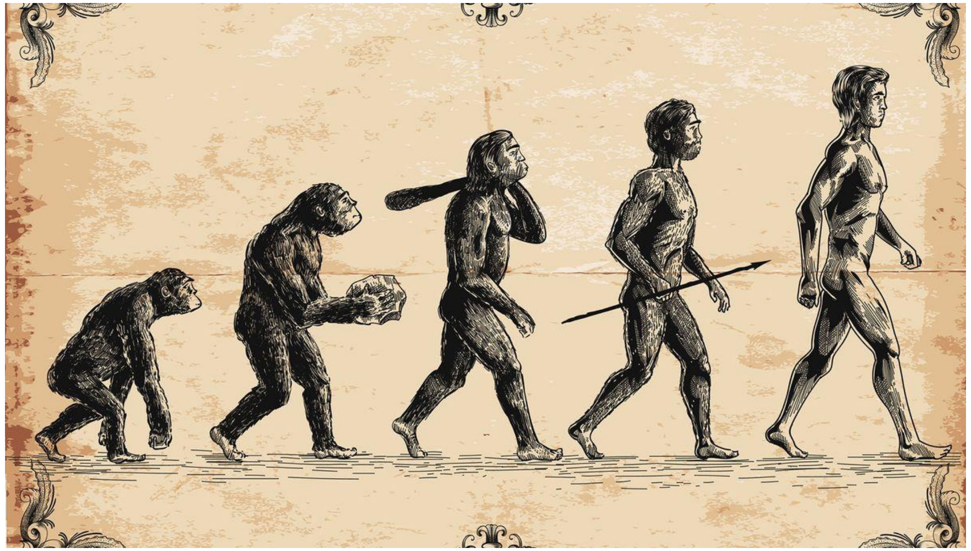
DIY

Secchi disc



Jackson Candle Turbidimeter
(unit JTU)





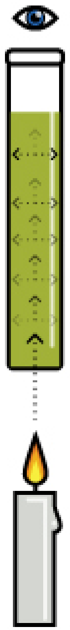
DIY

Secchi disc

SUPER DIY

Low-cost

Low-tech



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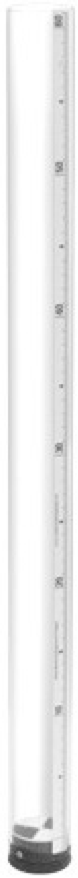
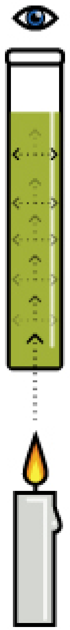
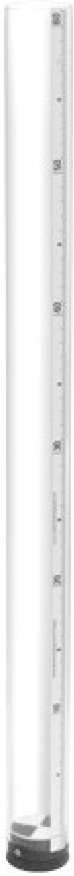


DIY

Secchi disc



Jackson Candle Turbidimeter
(unit JTU)



Too much low kill the low

Very too much low

Low useful

Low-accuracy

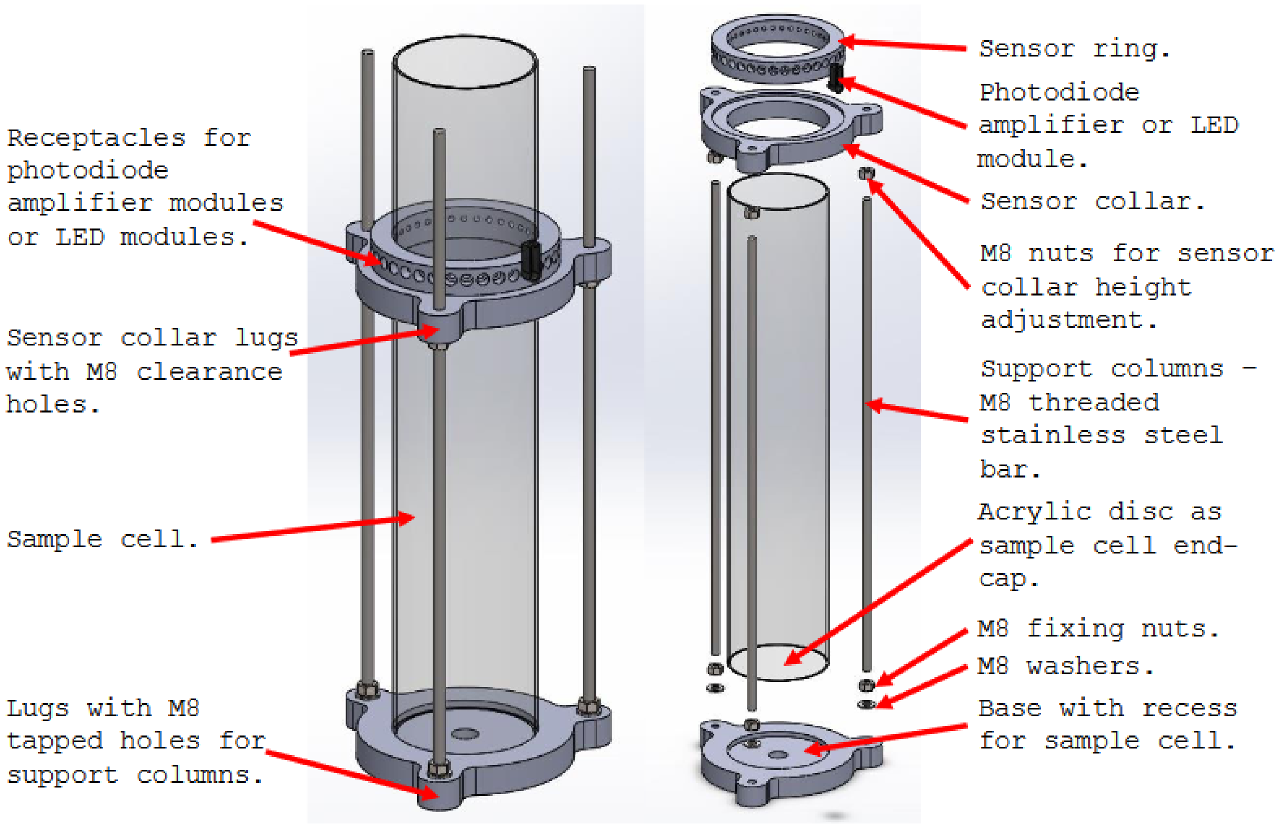


Figure 2. TARDIIS instrument assembly (left) and exploded view (right) showing the mounting system with support columns for the sensor collar containing the sensor ring.

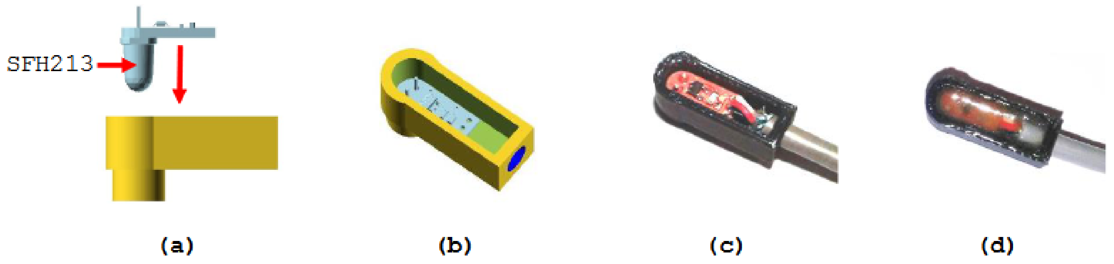


Figure 9. a) CAD model showing the photodiode amplifier PCB insertion into the module housing. b) A CAD model of the PCB located in the housing. c) The actual photodiode amplifier located in the 3D-printed module housing with cable attached. d) The module potted with epoxy resin.

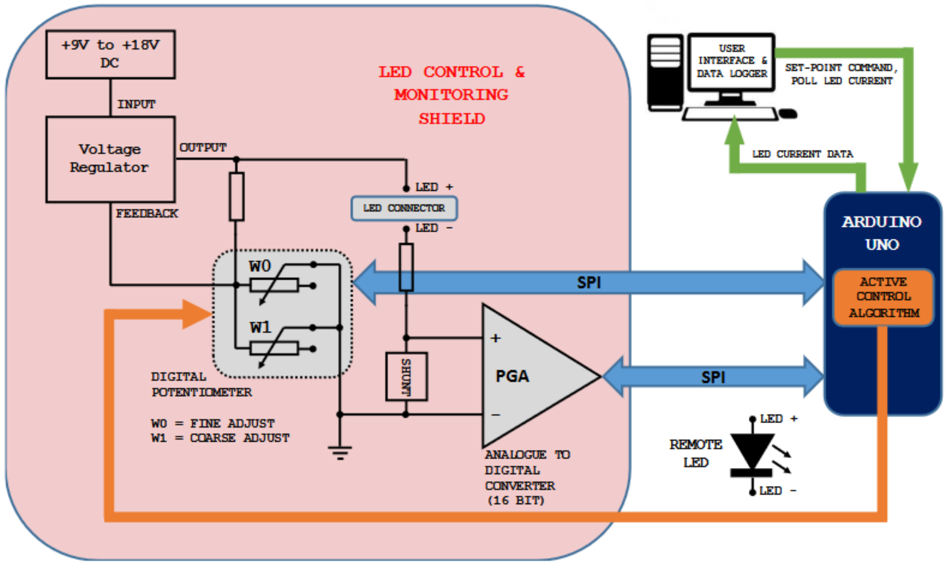


Figure 15. Conceptual circuit diagram of the LED control system. SPI is the serial peripheral interface for two-way communication between the Arduino UNO and the two chips (the DIGPOT chip and the ADC chip). W0 and W1 are the two potentiometer-wiper positions, controlled digitally via the SPI interface with the Arduino UNO. PGA is the programmable gain amplifier built into the front end of the ADC chip. The box labelled "SHUNT" is the shunt resistor across which the ADC measures a voltage drop. The active control algorithm converts the measured voltage into the LED current measurement.

Kitchener, Ben & Dixon, Simon & Howarth, Kieren & Parsons, Anthony & Wainwright, John & Bateman, Mark & Cooper, James & Hargrave, Graham & Long, Edward & Hewett, Caspar. (2019). A low-cost bench-top research device for turbidity measurement by radially distributed illumination intensity sensing at multiple wavelengths. HardwareX. 5. e00052. 10.1016/j.ohx.2019.e00052.

DIY +

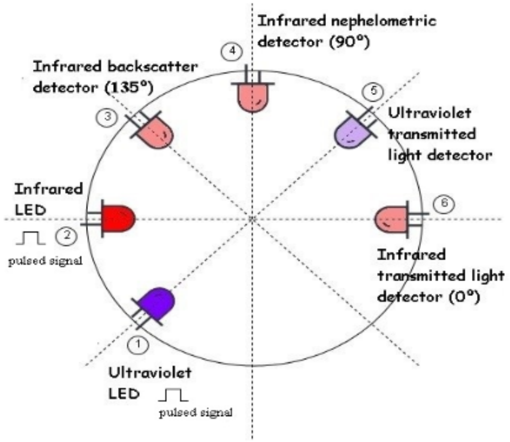


Figure 2. Schematic of the transducers' positions design. Different receptor positions relative to the light source provide different electrical responses. In the image are represented the IR LED (2) and the three types of detection: backscatter (3), nephelometric (4) and transmitted light (6). The UV emitter (1) and wideband receiver (5) are also presented.

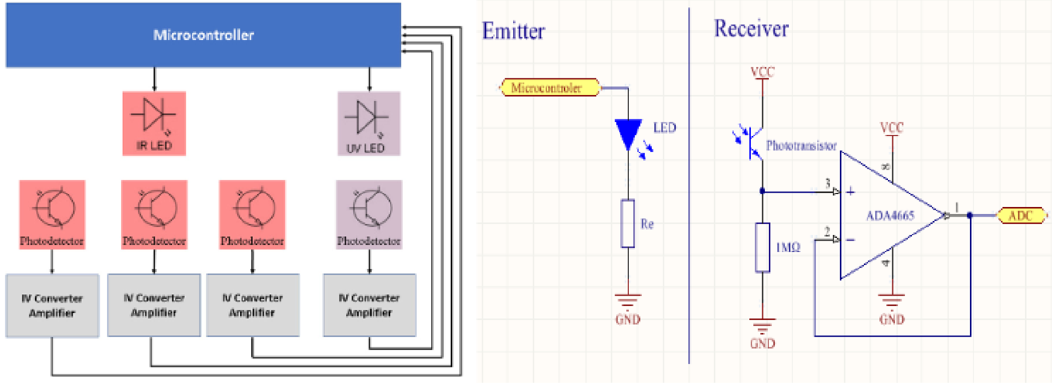


Figure 3. Hardware schematic of the sensor. A printed circuit board with the electronic instrumentation is integrated with the mechanical sensor structure and housing. The emitting hardware uses LEDs controlled by the microcontroller, with a serial resistor Re (different values from IR and UV LEDs to match their own current values) to settle the light intensity. The receiving hardware is composed of the phototransistors and I-V conversion resistors (Rr), and a buffer amplifier to reduce leakage currents when connected to the ADC of the microcontroller.

Figure 4. Turbidity optical sensor built in a radial configuration by 3D printing and filled with epoxy for submersion.

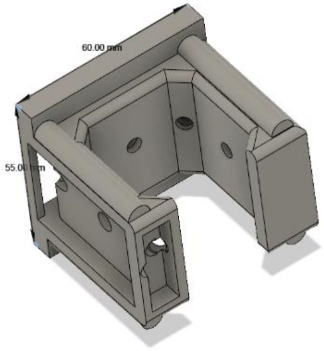


Figure A1. 3D model and dimensions of the sensor housing in Fusion360.

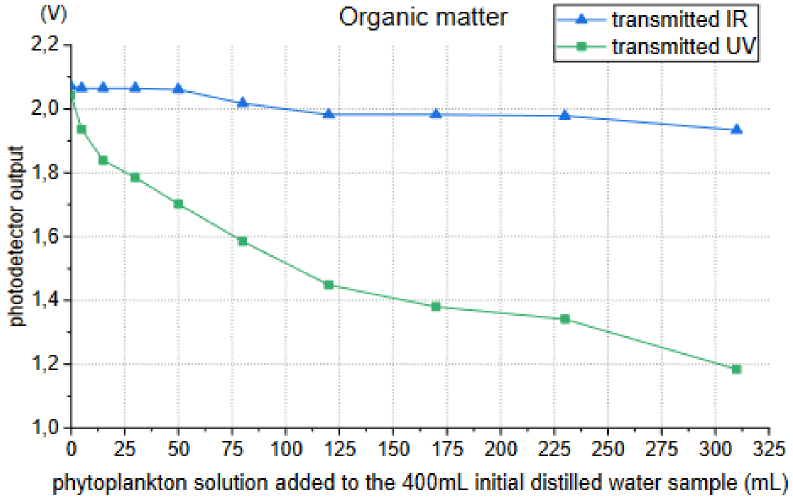


Figure 7. Transmitted IR and UV outputs when organic matter (phytoplankton) is added to water.

Matos, T.; Faria, C.L.; Martins, M.S.; Henriques, R.; Gomes, P.A.; Goncalves, L.M. Development of a Cost-Effective Optical Sensor for Continuous Monitoring of Turbidity and Suspended Particulate Matter in Marine Environment. Sensors ***2019****, 19, 4439. https://doi.org/10.3390/s19204439*

DIY ++

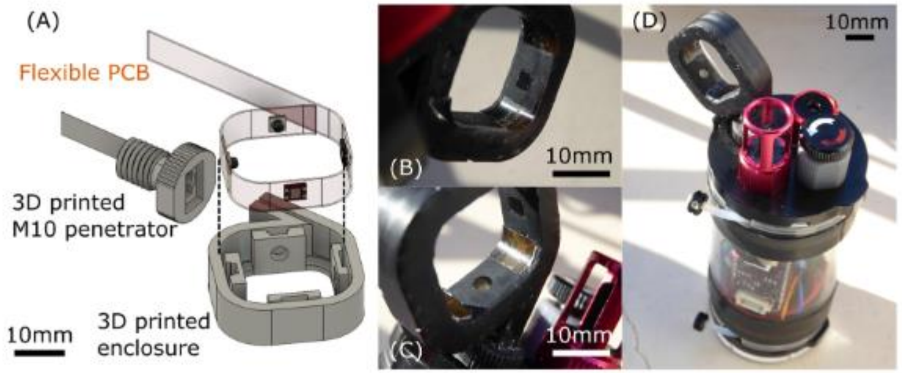


Figure 4. (**A**) CAD illustration of the GLI-2 sensor, with the flexible PCB hosting the two IR LEDs and the two photodiodes, the 3D-printed enclosure, and a 3D-printed M10 penetrator that makes the sensor compatible with Blue Robotics waterproof enclosures. (**B**,**C**) Close-up pictures of a photodiode and an LED optical port, respectively, after the PMDS overmolding step, to illustrate the good transparency and optical properties obtained with our method. (**D**) Implementation for in situ deployment with the electronics and LiPo battery protected behind a Blue Robotics two-inch diameter enclosure, showing the GLI-2 sensor head as well as additional pressure (depth) and temperature sensors.

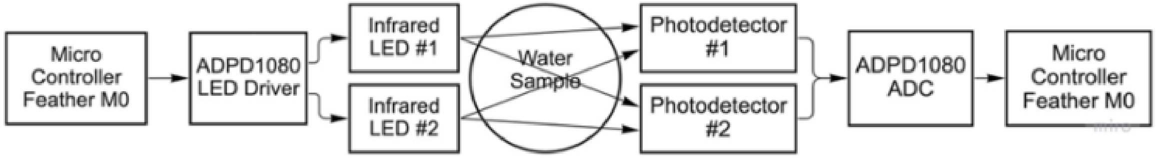


Figure 3. Block diagram of the OpenProbe GLI-2 sensor.

$$\text{GLI-2}_{\text{NTU}} = Cal_{slope}\sqrt{\frac{Active1 * Active2}{Reference1 * Reference2}} - Cal_0,$$

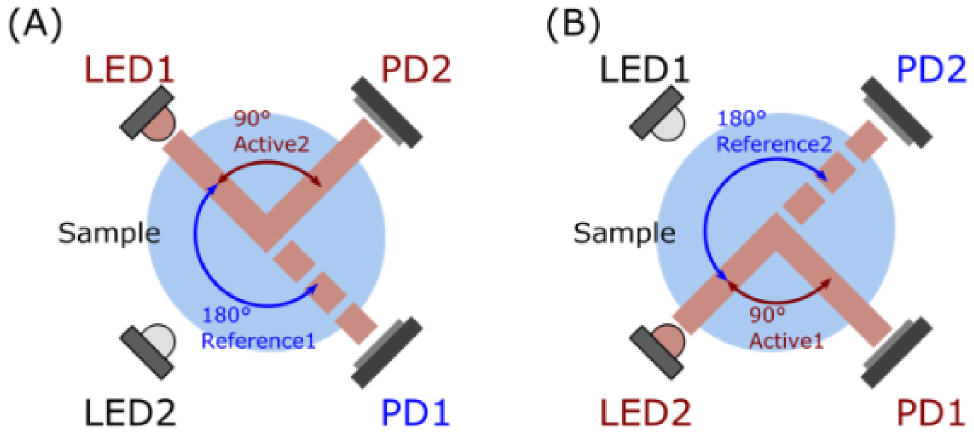


Figure 2. Illustration of the GLI-2 method, a ratiometric method based on a modulated 4-beam design. (**A**) Phase one: light source LED1 is on, photodetector PD2 measures the Active2 signal (90° nephelometric), and photodetector PD1 the Reference1 signal (180° attenuation). (**B**) Phase two: light source LED2 is on, photodetector PD2 is the Reference2 signal (180° attenuation), and photodetector PD1 is the Active1 signal (90° nephelometric).

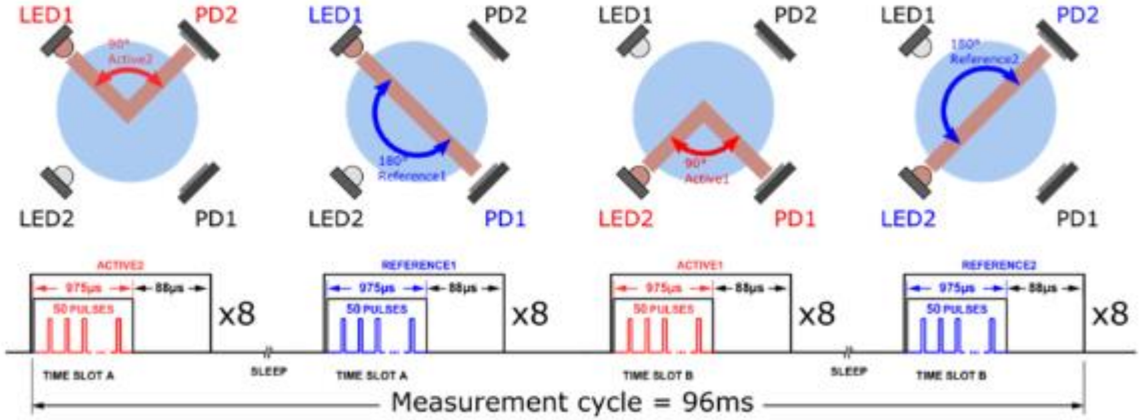


Figure 5. Measurement sequence implemented by the software to measure Active2, Reference1, Active1, and Reference2 signals and corresponding timing diagram illustrating the AFE operation. Each step was performed eight times to perform internal averaging, which allows to improve signal-to-noise ratio. Total measurement time in this configuration is 96 ms.

Sanchez, R.; Groc, M.; Vuillemin, R.; Pujo-Pay, M.; Raimbault, V. Development of a Frugal, In Situ Sensor Implementing a Ratiometric Method for Continuous Monitoring of Turbidity in Natural Waters. Sensors ***2023****, 23, 1897. https://doi.org/10.3390/s23041897*

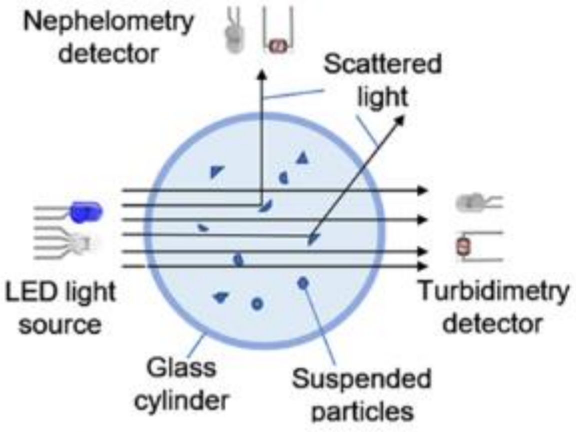


Figure 1. Diagram of operation of a turbidimeter and nephelometer.

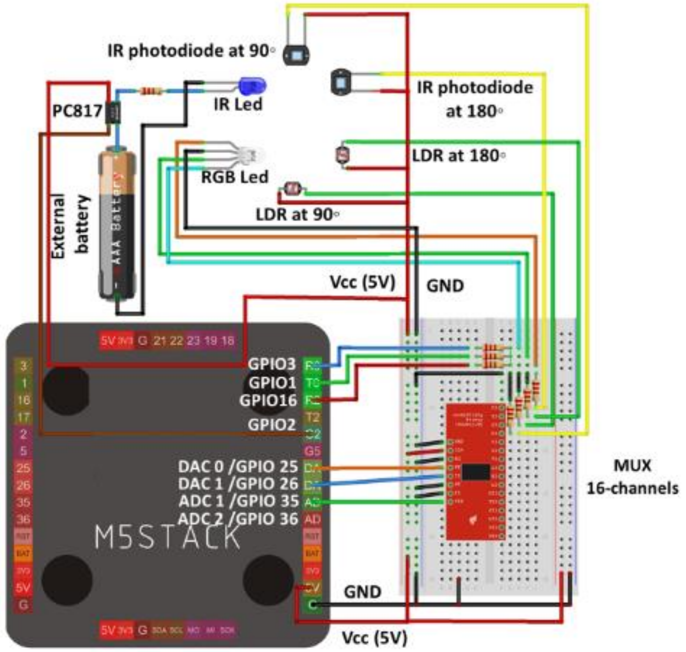


Figure 2. Electric scheme of the prototype.

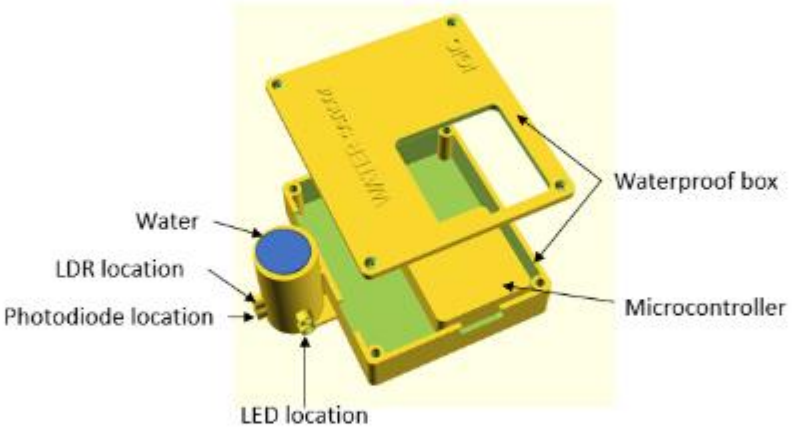
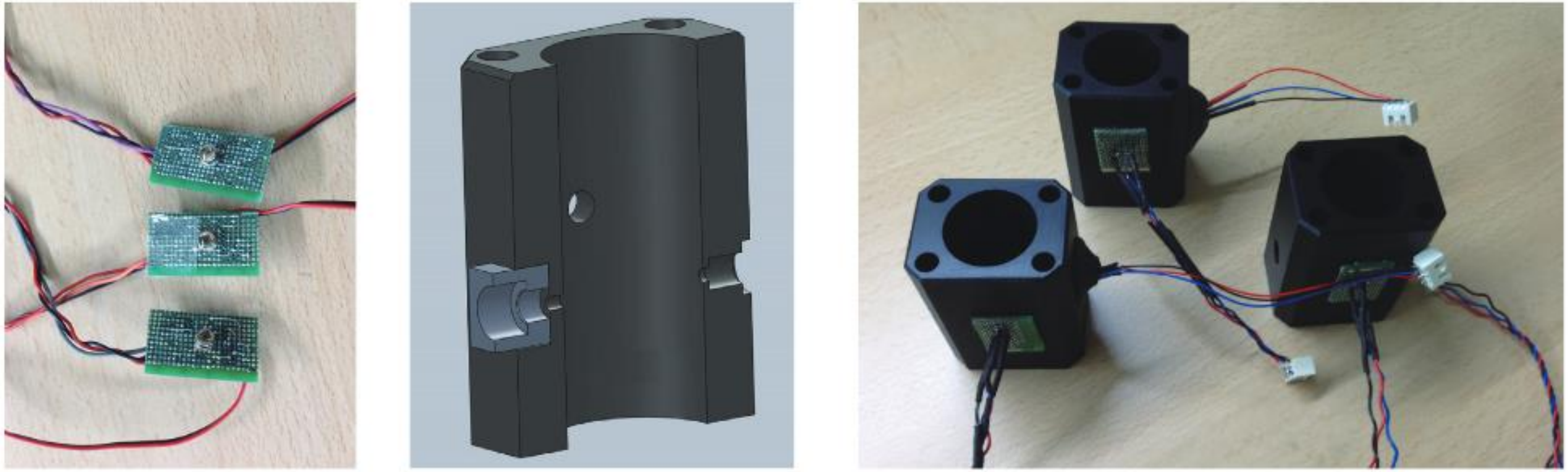


Figure 3. Scheme waterproof box.

Rocher, J.; Jimenez, J.M.; Tomas, J.; Lloret, J. Low-Cost Turbidity Sensor to Determine Eutrophication in Water Bodies. Sensors ***2023****, 23, 3913. https://doi.org/10.3390/s23083913*

DIY - -



(a) (b) (c)

Fig. 1. (Color online) Holder for measuring turbidity using wavelengths of 470, 670, and 850 nm: (a) LED light sources, (b) 3D model of holder, and (c) prototype holders.

Beom-Su Kim, Sungkwan Youm, and Yong-Kab Kim, Measurement of Turbidity Using an 850 nm Light-emitting Diode, Sens. Mater., Vol. 32, No. 12, 2020, p. 4169-4178.

DIY – Open Source

+ + +

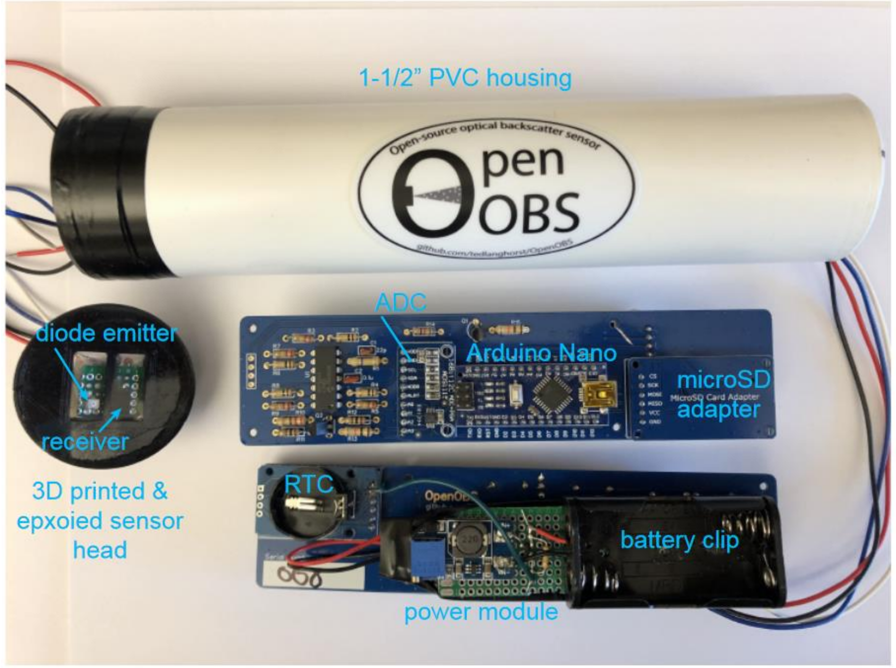


Figure 1: OpenOBS instrument. Parts shown include the housing with endcap installed, an example endcap that has not yet been installed, and the front and back of the circuit board with breakout boards and peripherals attached. A commercial watertight compression plug (not shown) is added to the right end to complete the housing.

Figure 6: Surf-zone deployment at the FRF site in Duck, NC (May 2021). (A) Sensors were mounted on poles jetted into the surf zone at low tide. Deployments lasted 24-48 hours, and maximum inundation during high tide was on the order of 1 m. (B) Mounting detail.

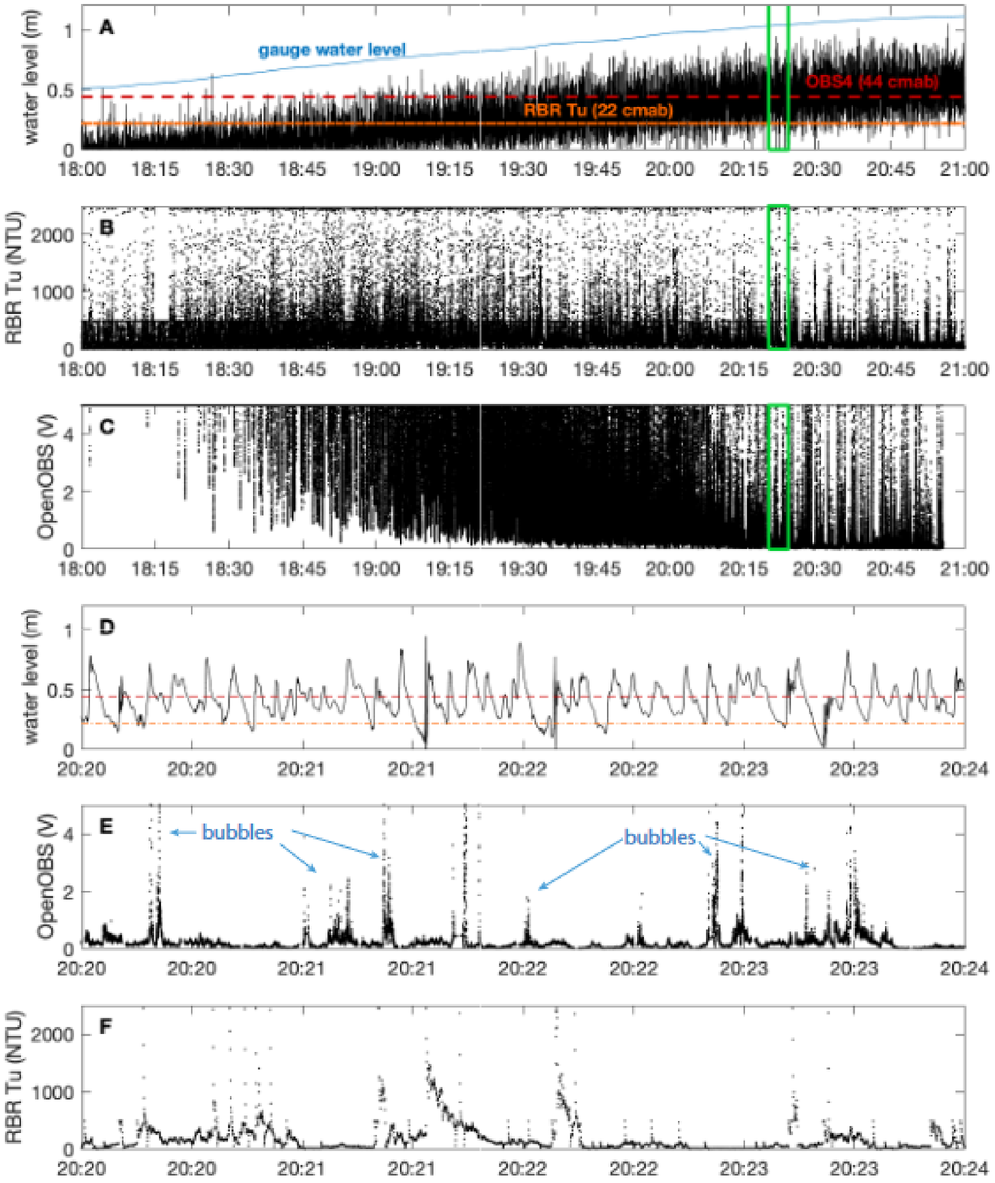


Figure 7: Surf zone test results from 13 May. (A) Gauge water level (from FRF pier, blue) and measured water level at one of the two instrument poles (black). Elevations of OBS4 and a commercial sensor (RBR Tu) are shown. (B) Commercial sensor turbidity results (16 Hz). (C) OpenOBS results (200 Hz). (D) Expanded view of the water-level record for 4 minutes on 13 May. (E) Expanded view of the OpenOBS record. (F) Expanded view of the commercial sensor turbidity record.

Eidam, Emily & Langhorst, Theodore & Goldstein, Evan & McLean, McKenzie. (2021). OpenOBS: Open-source, low-cost optical backscatter sensors for water quality and sediment-transport research. 10.31223/X5KC9W.

DIY – Open Source + + +

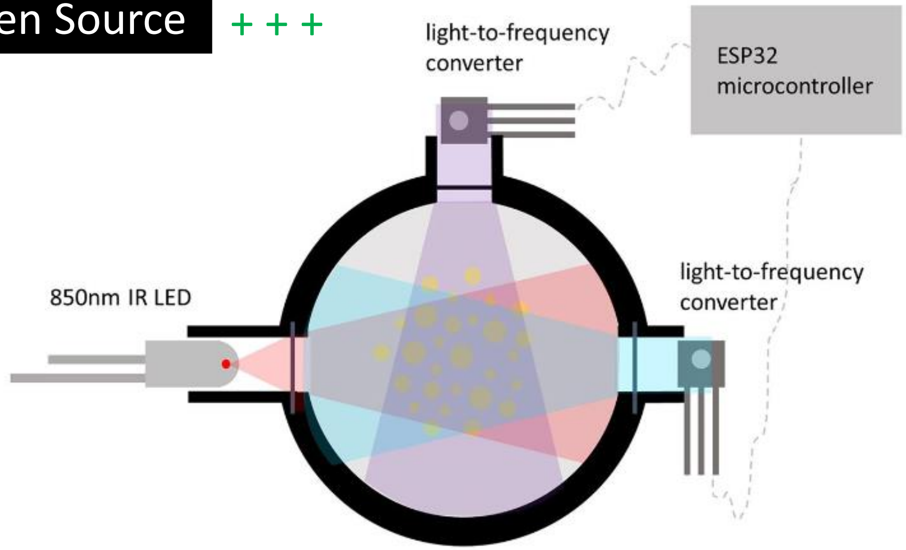


Figure 8. Sensing principle behind the open-source turbidity sensor.

Figure 9. Open-source turbidity sensor—second prototype. **(a)** Closed sensor with external PVC housing. **(b)** Internal electronics of the sensor.

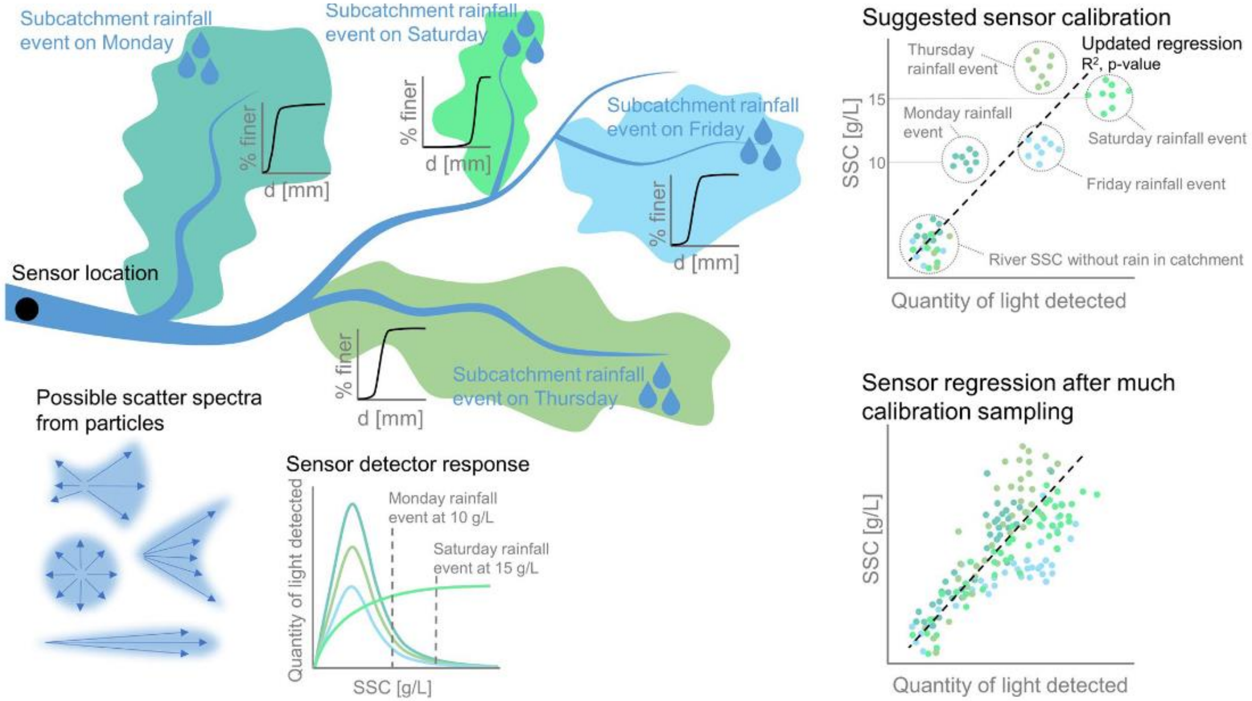
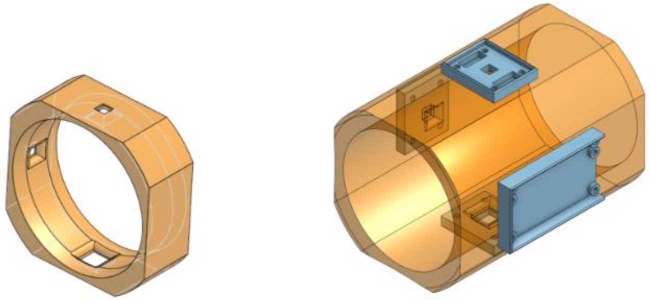


Figure 7. Conceptual scheme of a direct calibration of SSC to the light detected by a sensor in a river with several subcatchments that all have different sediment types and grain size distributions and therefore, emit different scatter spectra. In this example, every subcatchment experiences an isolated rainfall event on a different day. The sensor detectors at the downstream end of the river have a different light intensity response depending on the sediment type. After sampling many different events, a single calibration curve representative of the different subcatchment sediment sources and their activation frequencies can be obtained.

Droujko, J., Molnar, P. Open-source, low-cost, in-situ turbidity sensor for river network monitoring. Sci Rep ***12****, 10341 (2022). https://doi.org/10.1038/s41598-022-14228-4*

DIY -

Figure 1. Amphenol TST-10 (**left**) and TSD-10 (**right**). TSW-10 is similar to the TSD-10 (not pictured) (images from Amphenol).



(a) (b)

Figure 8. Nephelometric sensor mounts for clear pipes. **(a)** Initial design. **(b)** Revised design including PCB mounts and reduced ambient light.

Figure 9. Sensor 18 configured for laboratory calibration.

« light intensity at 90°, 180° + dark reading @ 90° each 6sec »

$$NTU = c_1 \times d_0 + c_2 \times d_{90} + c_3 \times d_{180} + \epsilon$$

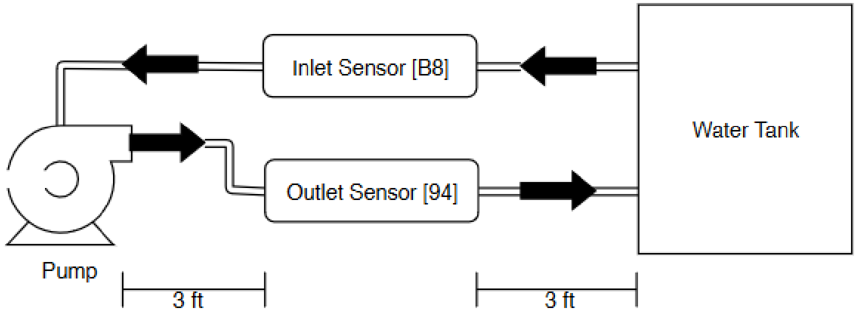


Figure 13. Diagram of pumped tank test.

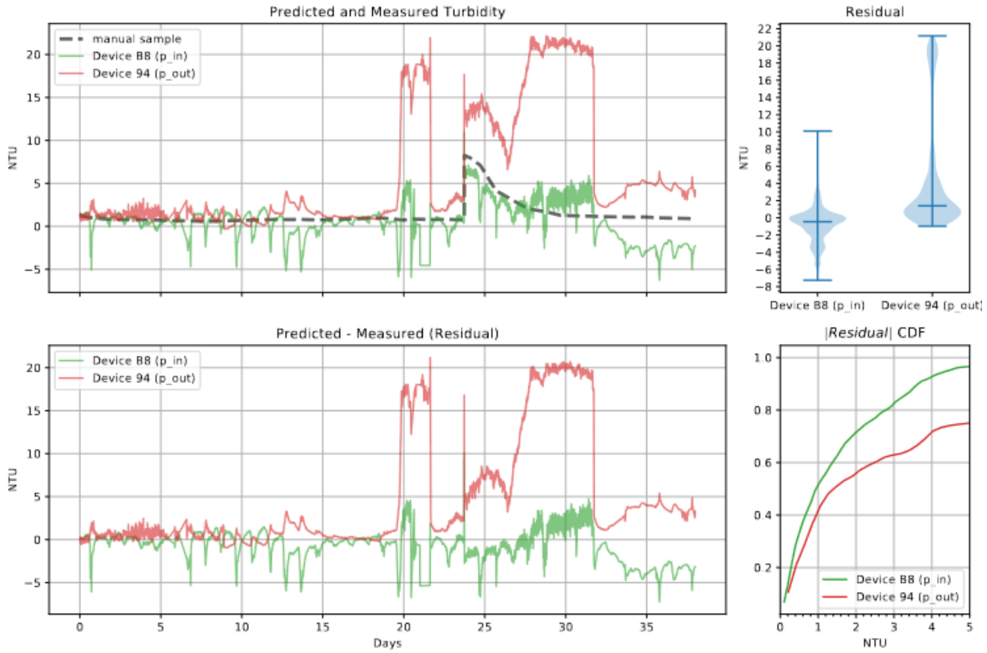


Figure 14. Pumped tank low-cost continuous turbidity monitor predictions from the pump inlet (p_in) and outlet (p_out) and manual measurements from a hand-held turbidimeter showing all collected data (days 0 through 37).

Gillett, D.; Marchiori, A. A Low-Cost Continuous Turbidity Monitor. Sensors ***2019****, 19, 3039. https://doi.org/10.3390/s19143039*

SEN0189 (DFROBOT) turbidity sensor : 7 articles

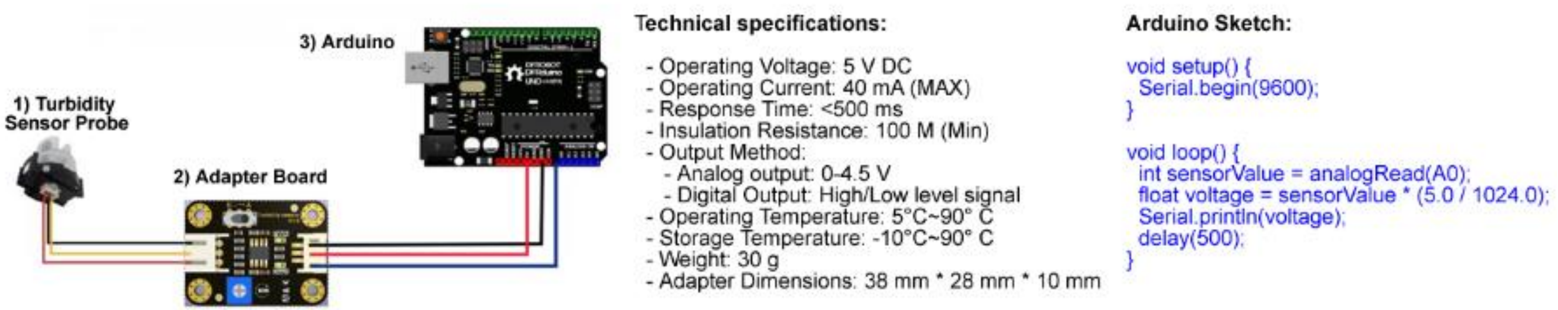


Figure 2. Wiring diagram, setup, and specifications for the DF Robot Gravity analogue turbidity sensor.

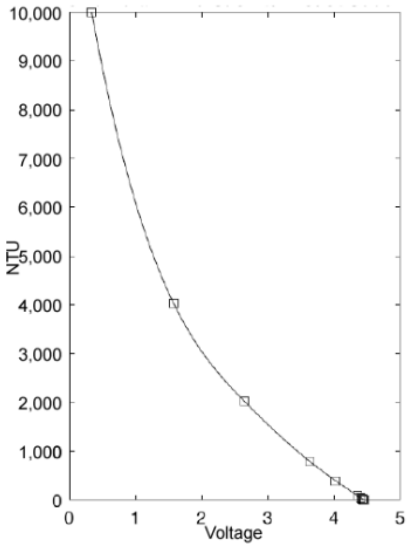
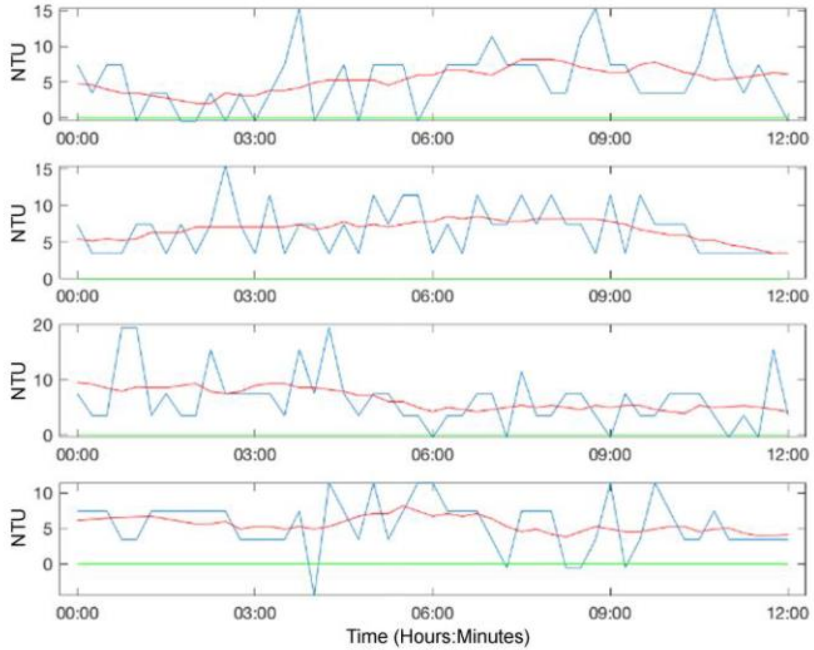


Figure 11. Voltage versus Nephelometric Turbidity Units (NTU): Least squares fit.

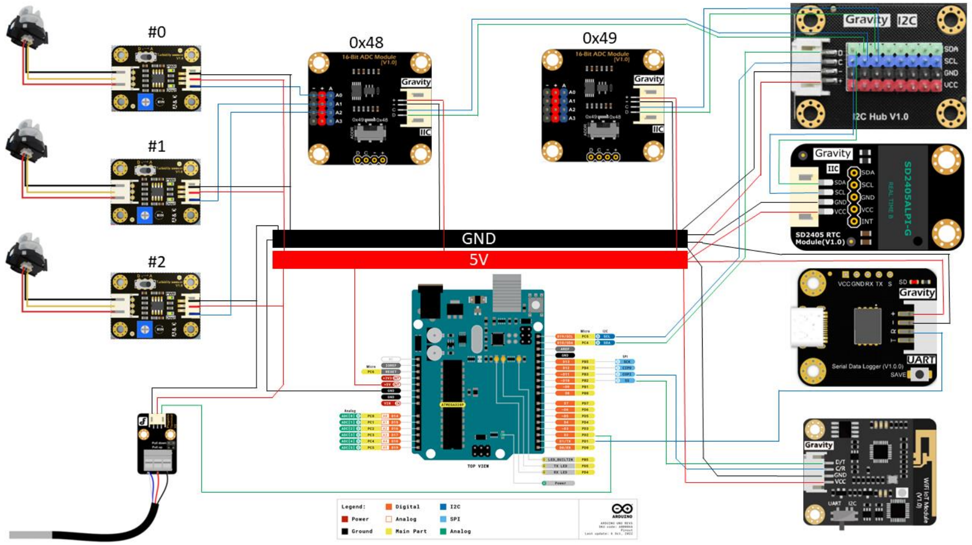
Figure 9. Encasing and waterproofing the turbidity sensor.



Trevathan, J.; Read, W.; Schmidtke, S. Towards the Development of an Affordable and Practical Light Attenuation Turbidity Sensor for Remote Near Real-Time Aquatic Monitoring. Sensors ***2020****, 20, 1993. https://doi.org/10.3390/s20071993*

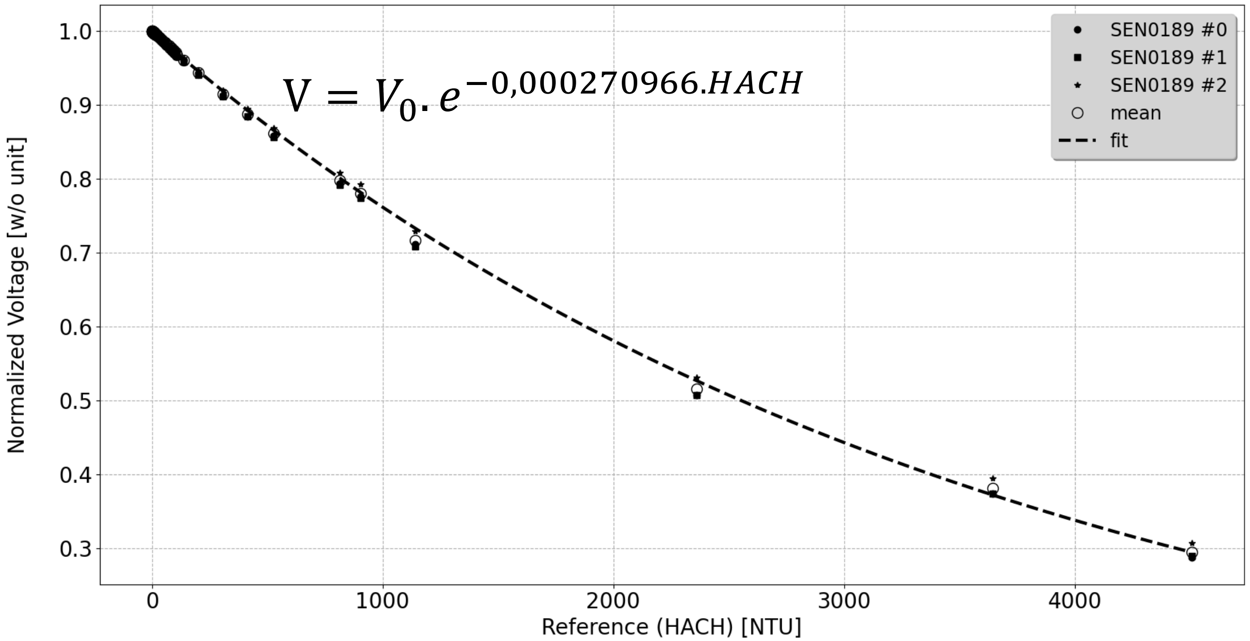
DIY – Open Source

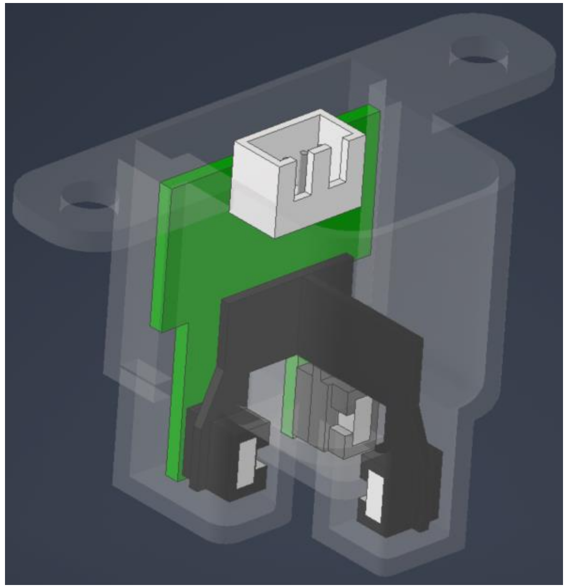
Low-cost and autonomous field optical turbidimeter (open source?) – Matthias Jacquet



Soon

- Experiments with other particles (clay, mud, glass beads)
- Temperature effect
- Add 90° photodetector + reverse signal to find particle size





- Turbidity measurement :
  - Several meas. principles, methods, standards, units, …
  - Hard to standardize, but complementary when study in details natural particles

- DIY :
  - lower prices, increase number od deployments in the same time
  - manage manufacturing, maintenance if break
  - share and improve (hardware, software) when open source
  - but take a (long) time of engineer(s)/technician in dev. phase

Thanks!