VISLAB Low-Angle Scattering Meter

Designing and Building Ocean Optical Instruments

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IOCCG SLS Hyderabad – 11 November 2024

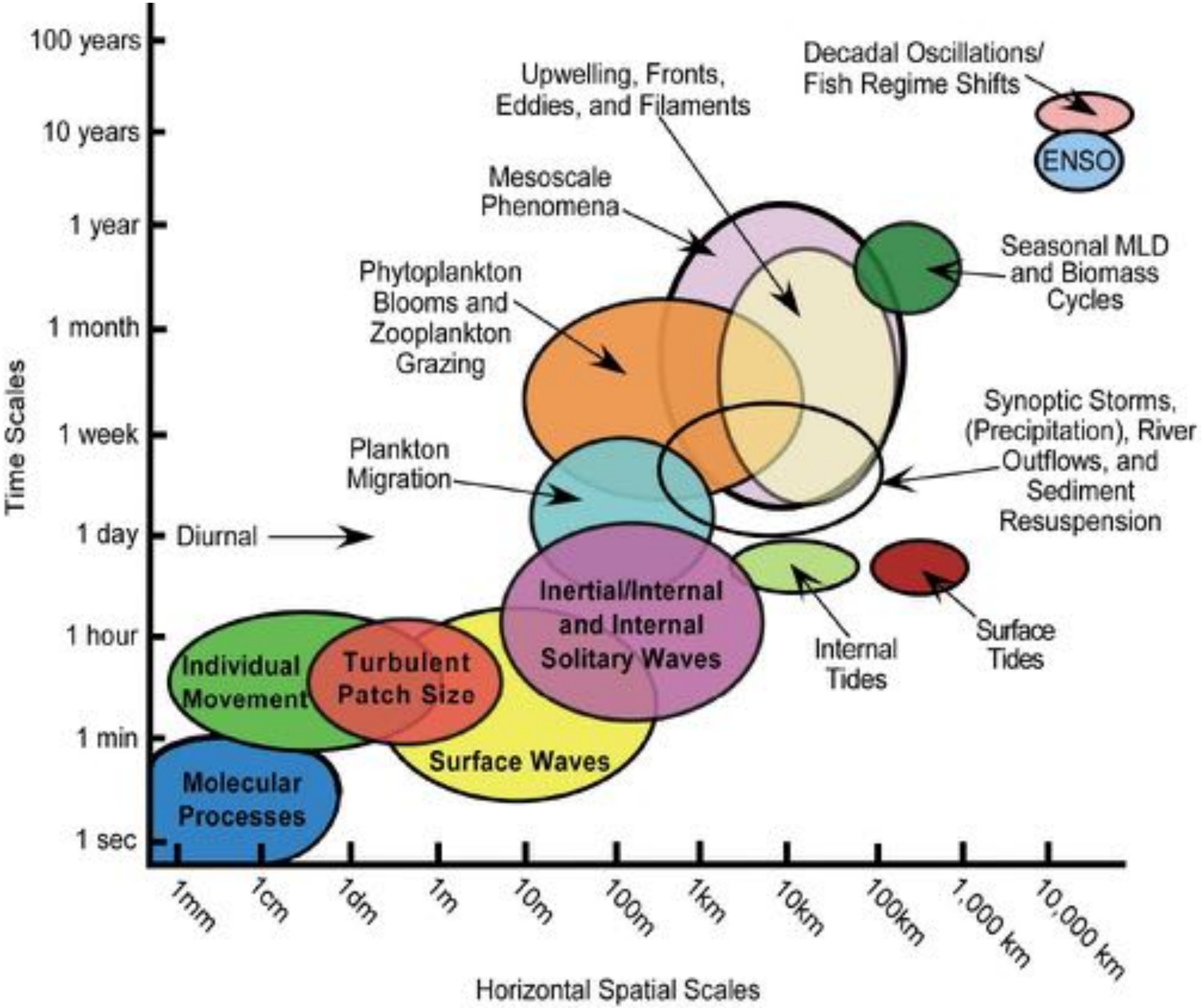
Why use optics to study the ocean?

In situ: compact active sensors on a wide array of platforms (IOPs, fluorescence), sub-meter and sub-second scales

Remote sensing: satellites that measure ocean color, global and daily scales

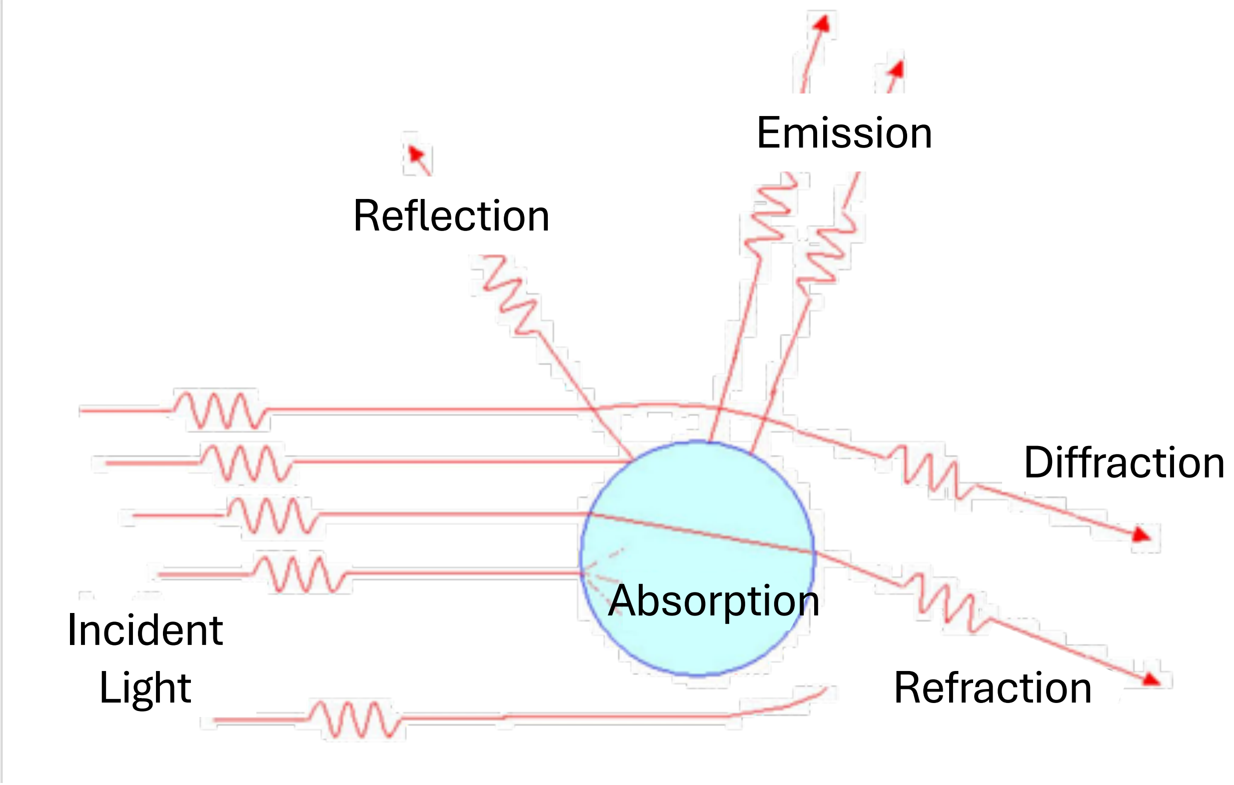
In situ: radiometers that measure ocean color, sub-meter and sub-second scales

<u>Additional appeal: in situ sensors are low power and versatile, e.g., deploy backscattering sensor on gliders and floats</u>



(Chang and Dickey)

Light interactions with matter in the ocean



Scattering is change in direction of photon via reflection, diffraction, refraction.

Absorption is the removal of photon and conversion of its energy to molecular energy (thermal, chemical, fluorescence emission).

Interaction of light with matter in the ocean can be quantified in terms of "inherent optical properties" (IOPs), that are properties of the medium and do not depend on the ambient light field.

Particle size, shape, and composition are important drivers of optical properties, especially scattering.

Pigments and other molecules absorb and fluoresce; for example, specific pigments indicative of species/group.

Challenge: can we use optical properties to predict properties of the particles, for example size, composition, specific types of phytoplankton?

The challenge is to understand relationships between optical properties and material properties

?

Given material (e.g., particles), describe optical properties

<u>Direct “forward” problem</u>
Given a dragon, describe its tracks.

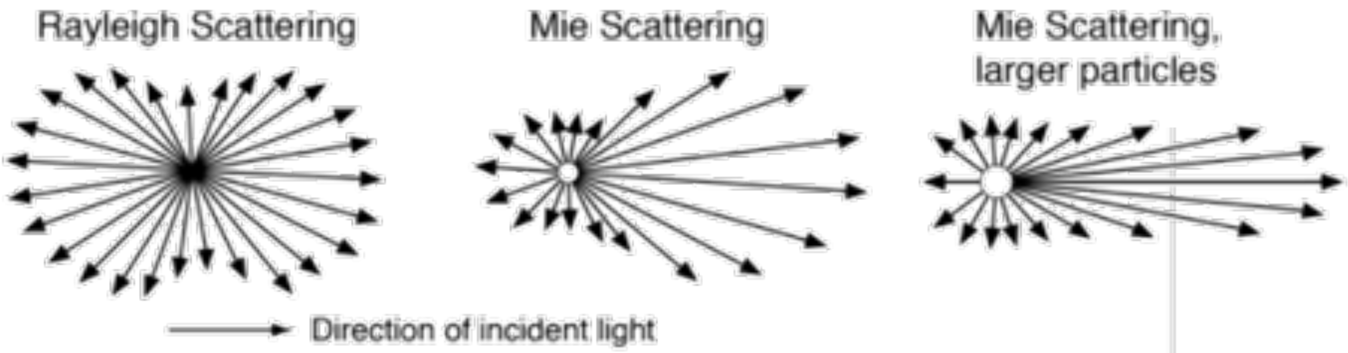
?

Measure optical properties, describe material properties

<u>Inverse problem</u>
Given a set of tracks, describe the dragon.

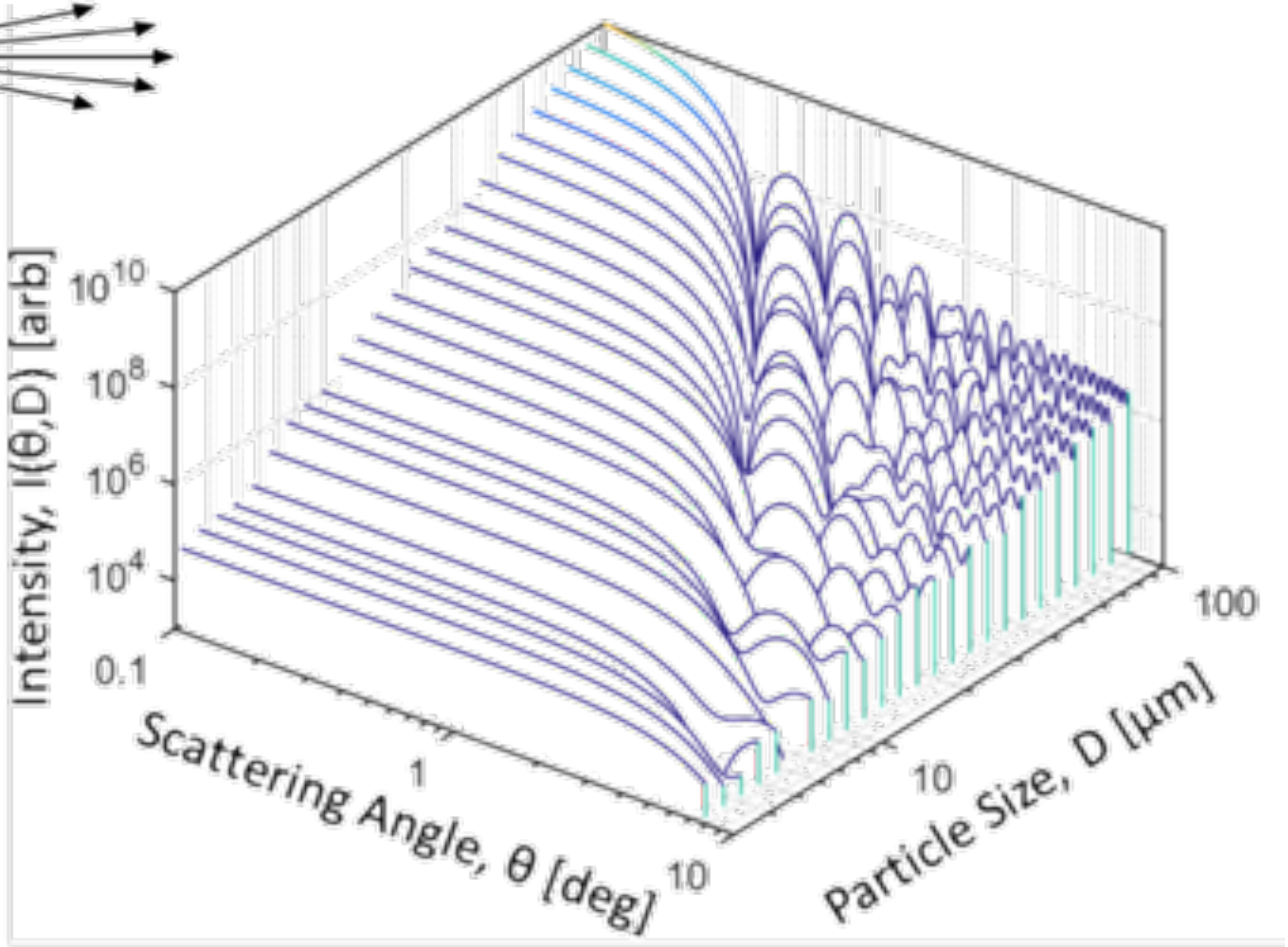
Bohren and Huffman (1983)

Scattering dependence on particle size

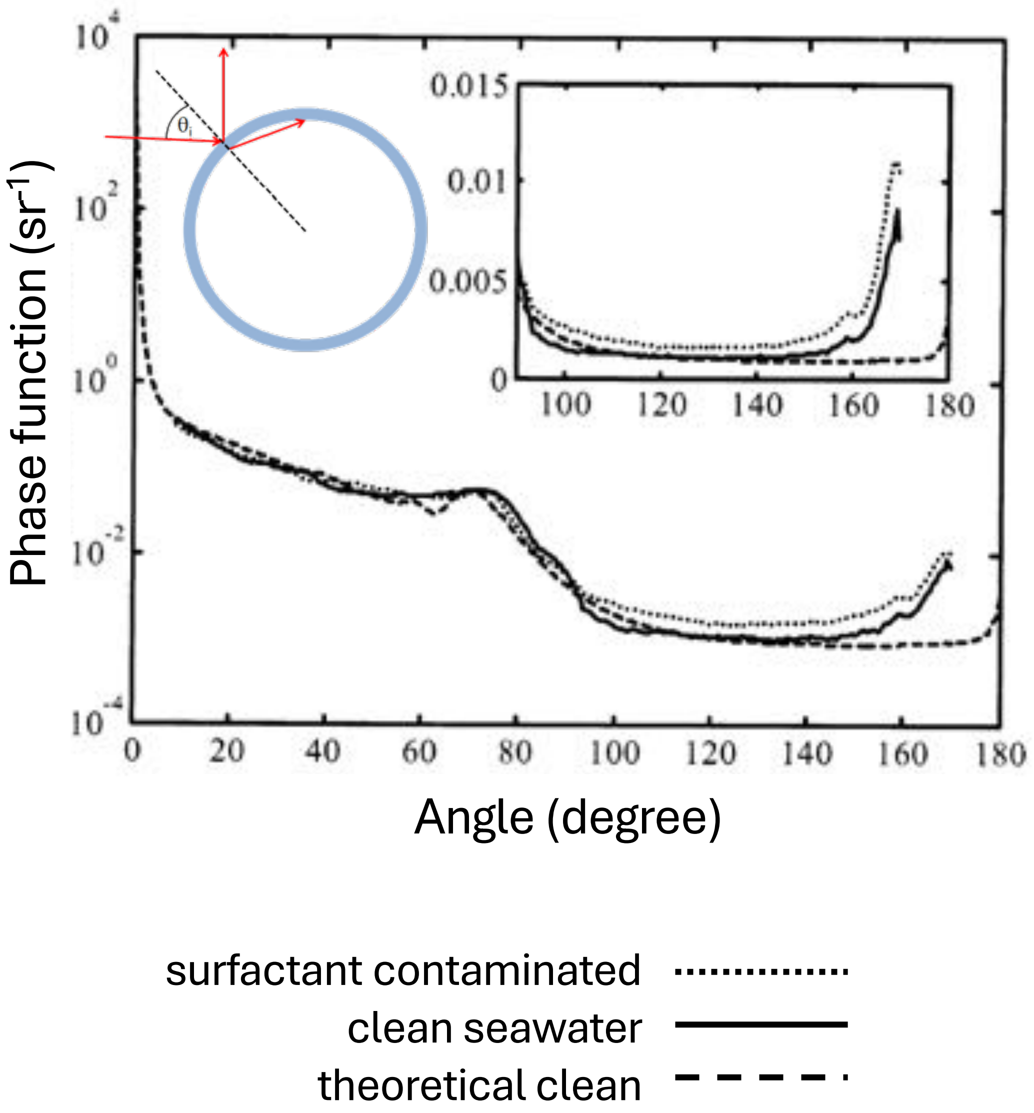


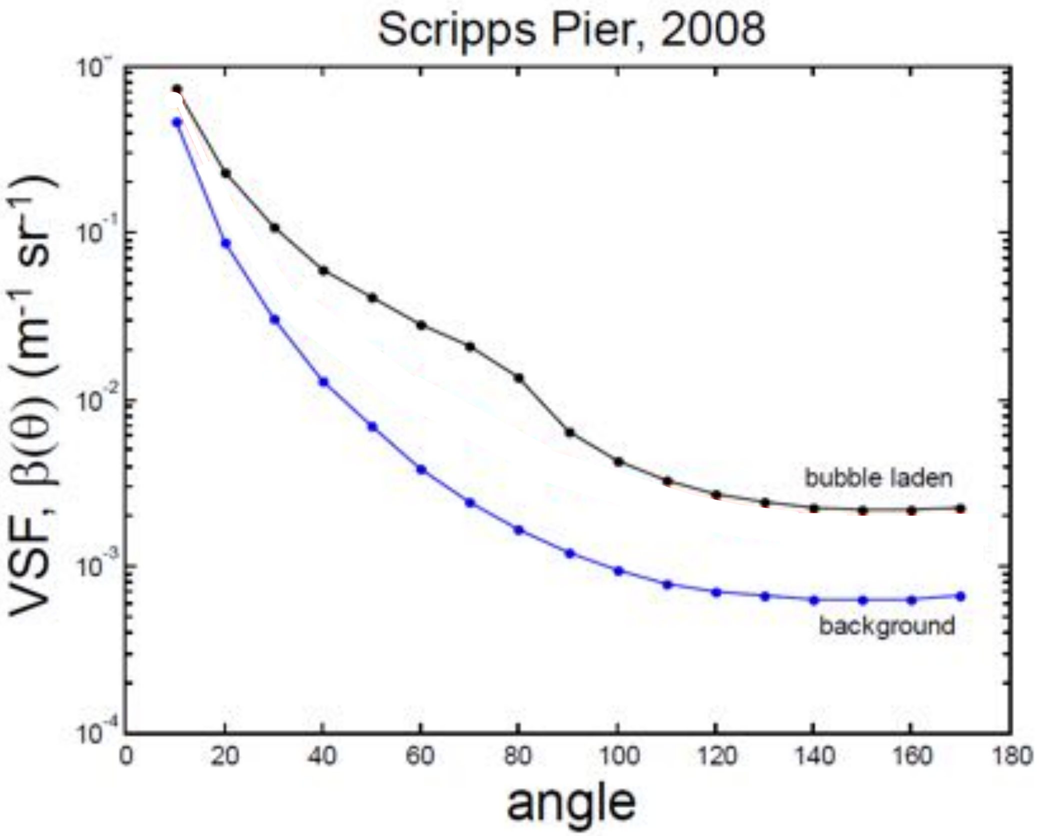
Angular dependence of scattering depends on particle size and can be predicted by theory (e.g., Mie) → "inversion algorithm"

Use measurements of that scattering to estimate particle size characteristics → "inversion algorithm"



Scattering by bubbles and sediments





How can bubbles vs background be distinguished using simple measurements?

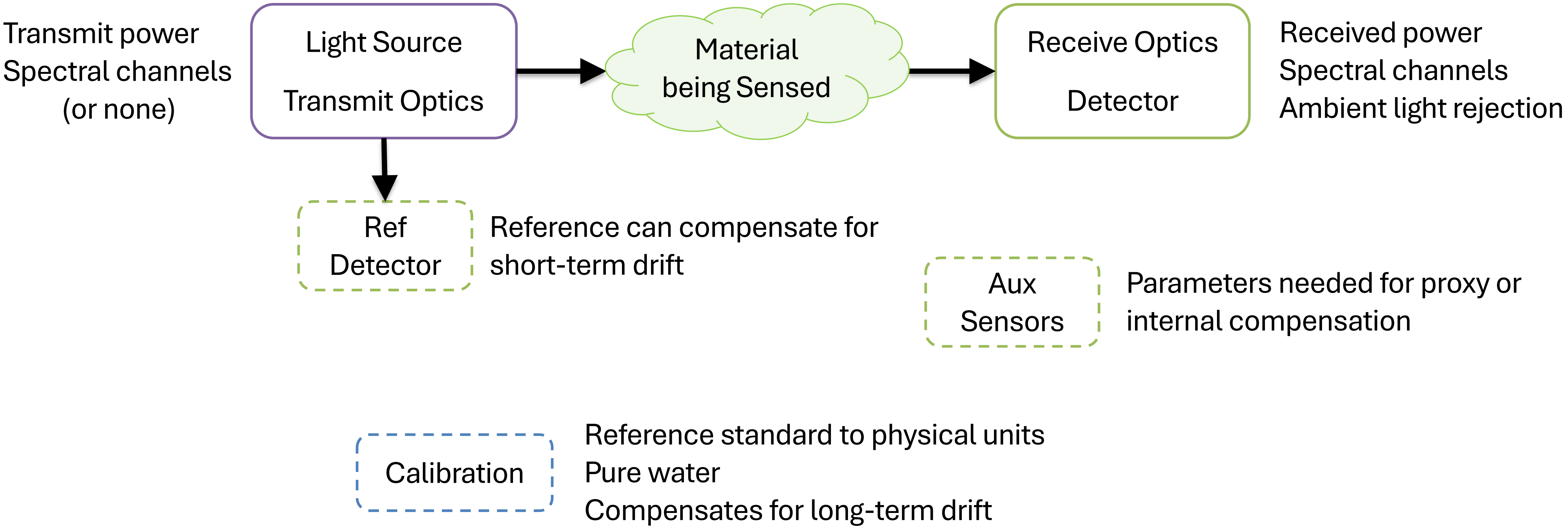
Sediments?

Zhang et al. (2002)

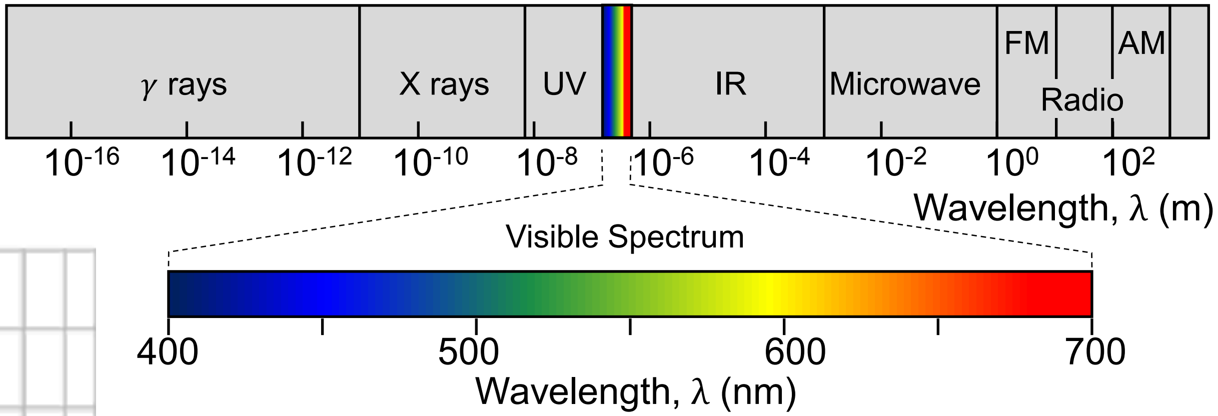
Mobley OOB (2022)
VSF Figure from M. Twardowski, see also Twardowski et al. (2012)

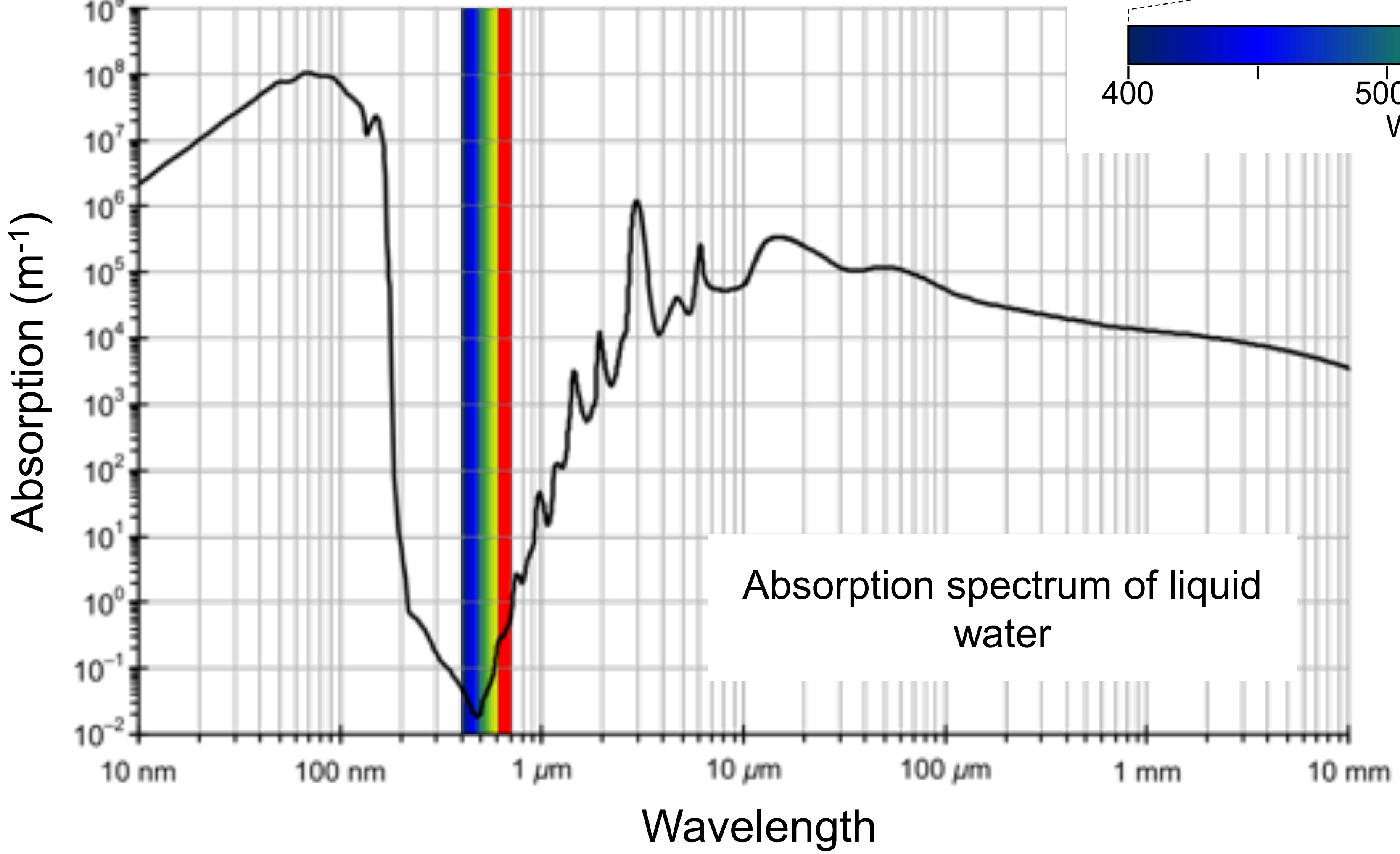
Basic sensor concepts

Active: Instrument has built-in source
Passive: Light is external to instrument (e.g., sun)



Visible / UV-Vis





We're generally concerned with the relatively narrow window from UV-VIS-NIR where water absorption is not dominant.

https://commons.wikimedia.org/wiki/File:Absorption_spectrum_of_liquid_water.png

Measuring Light: Radiometry

Radiometry	The science of measuring electromagnetic (radiant) energy

Detectors

Thermal – response proportional to energy
(light absorbed and converted to heat—thermopile)

Quantum – response proportional to number of photons
(photoelectric effect)   MOST COMMON

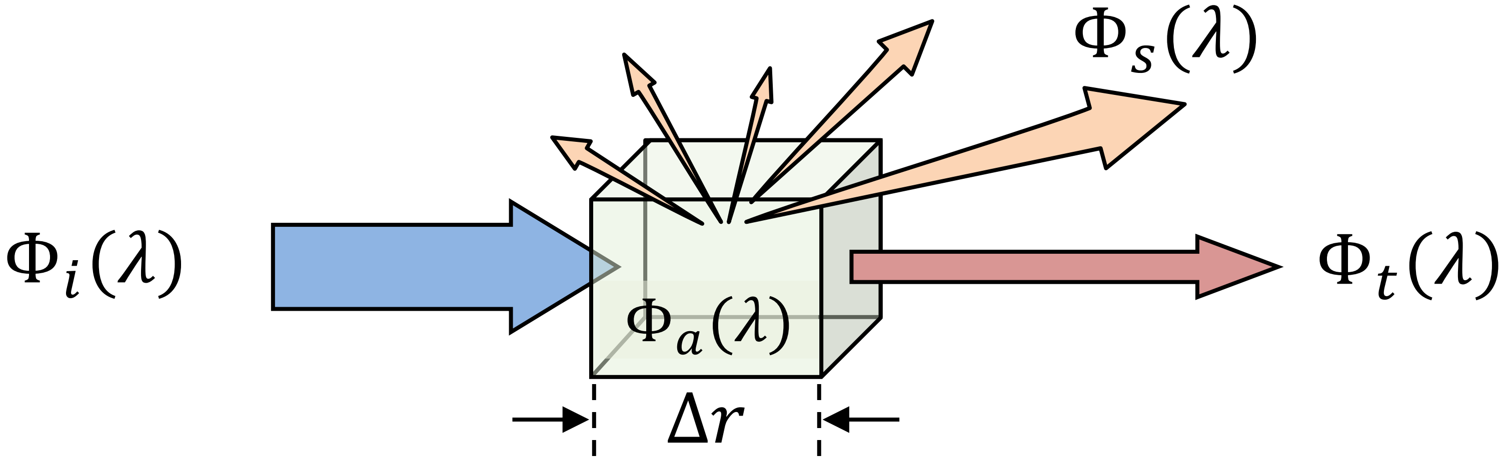
Two common ways to talk about optical power

Radiant power	Φ_e	[W]	power = energy per time
Spectral power	$\Phi_{e,\lambda}(\lambda)$	[W nm^{-1}]	power per wavelength

We often consider sources or detectors are band-limited (or use an optical bandpass) so total power is integral of spectral power over wavelength.

Defining Inherent Optical Properties

IOPs are properties of the medium and do not depend on the ambient light field.



Conservation of Energy $\Phi_i(\lambda) = \Phi_a(\lambda) + \Phi_s(\lambda) + \Phi_t(\lambda)$

Define fraction of power absorbed and scattered

Absorptance $A(\lambda) = \dfrac{\Phi_a(\lambda)}{\Phi_i(\lambda)}$ Scatterance $B(\lambda) = \dfrac{\Phi_s(\lambda)}{\Phi_i(\lambda)}$ [unitless]

Absorption and scattering coefficients are defined <u>per unit distance</u>

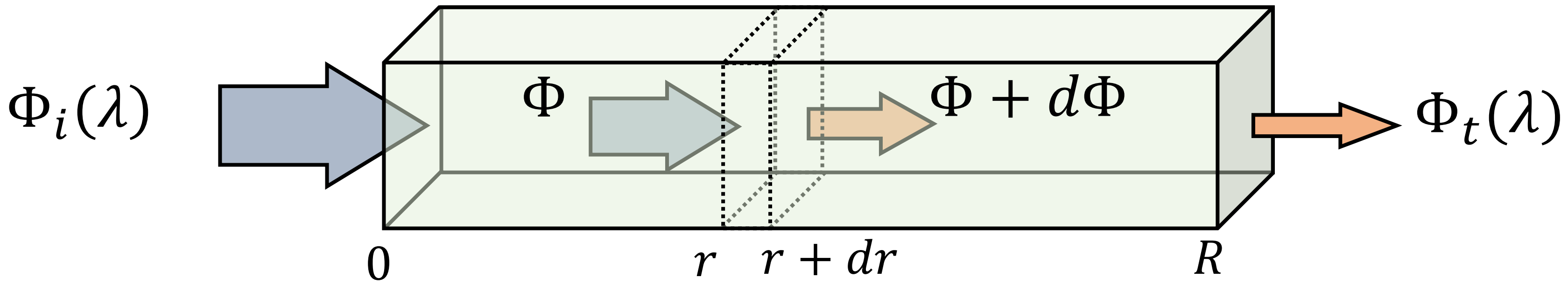
$a(\lambda) = \lim\limits_{\Delta r \to 0} \dfrac{\Delta A(\lambda)}{\Delta r} = \dfrac{dA(\lambda)}{dr}$ $b(\lambda) = \lim\limits_{\Delta r \to 0} \dfrac{\Delta B(\lambda)}{\Delta r} = \dfrac{dB(\lambda)}{dr}$ $[\mathrm{m}^{-1}]$

And we also define “beam attenuation” as the sum of the absorption and scattering coefficients

$c(\lambda) = a(\lambda) + b(\lambda)$

Example instrument: beam attenuation (transmissometer)

Reality is that instrument has some NON-infinitesimal pathlength R



In the same way the other coefficients were defined, i.e.,

$$a(\lambda) = \frac{dA(\lambda)}{dr}$$

Think about attenuance as fraction of power lost through dr

$$\mathrm{c}(\lambda) = \frac{dC(\lambda)}{dr} = \frac{-\frac{d\Phi}{\Phi}}{dr}$$

Integrate the attenuation along instrument path

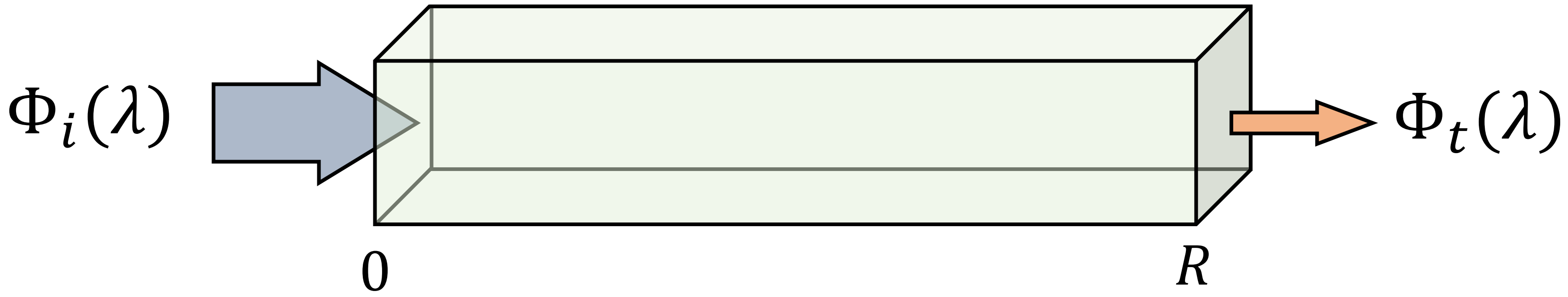
$$\int_0^R \mathrm{c}\, dr = -\int_0^R \frac{d\Phi}{\Phi(r)}$$

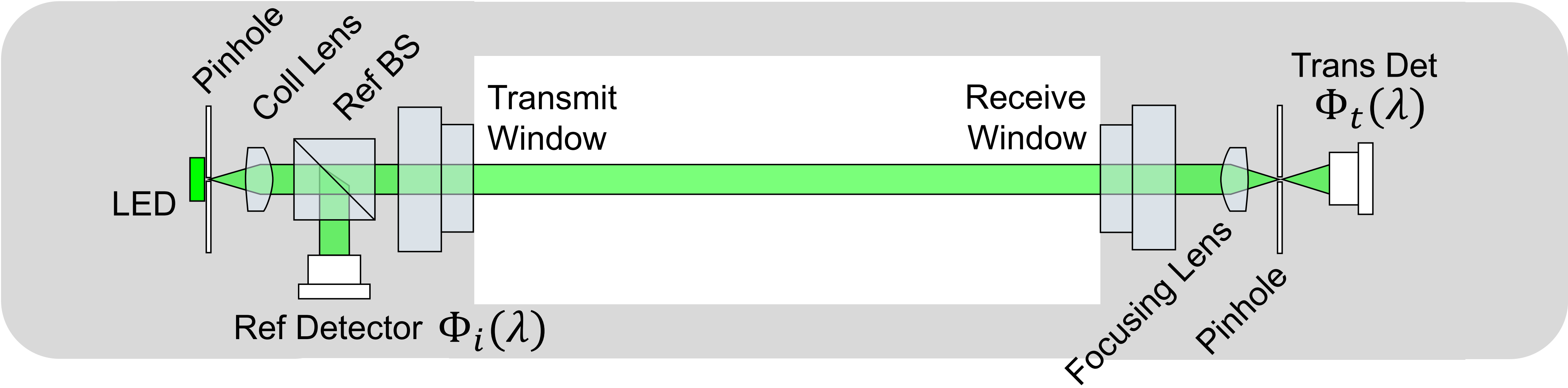
$$cR = -(\ln \Phi_t - \ln \Phi_i)$$

$$\boxed{c = -\frac{1}{R}\ln\frac{\Phi_t}{\Phi_i}}$$

Now we just need to build an instrument with light source that measures Φ_t and Φ_i…

Example instrument: beam attenuation (transmissometer)





Some scattered light also reaches detector since the pinhole can't be infinitesimally small!

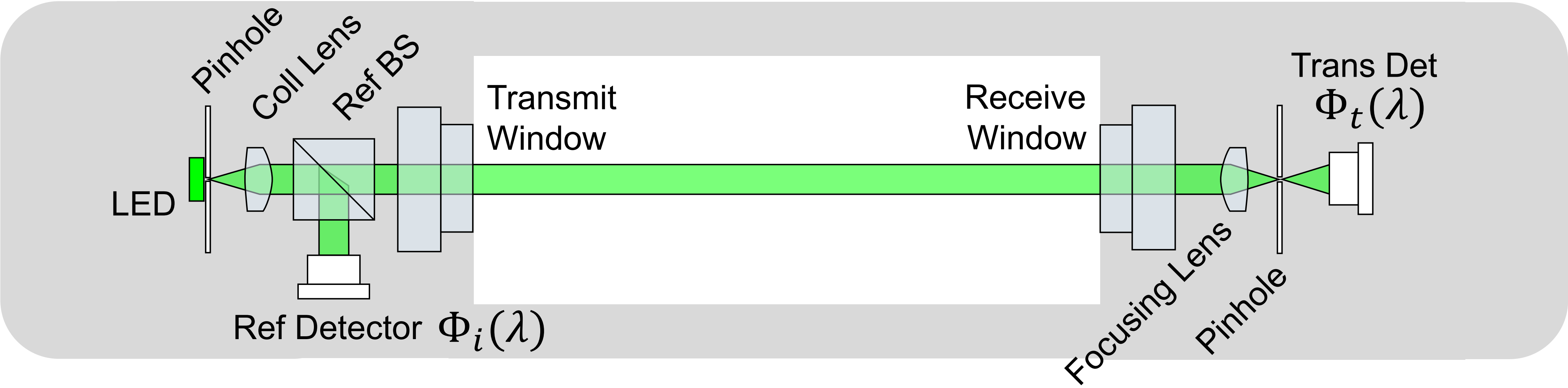
What other factors go into a design?

Spectral characteristics of source LED and photodetector

Durability, maintaining alignment of optics

Pathlength and signal (recall ac-s lab!) $$c = -\frac{1}{R}\ln\frac{\Phi_t}{\Phi_i}$$

Calibration and data processing



Common In Situ Ocean Optics Proxies

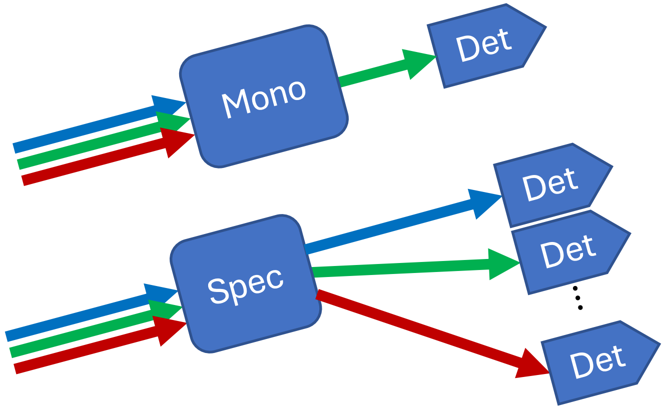
Attenuation	beam-c	How much stuff?
	c(λ)	PSD slope → particle size
Scattering	Turbidity, b, bb	How much stuff?
	Fwd VSF	Particle sizing (PSD)
	bb/b (VSF shape)	Particle composition
Absorption	Dissolved	How much DOM, refractory/labile
	Particles	How much pigment, what pigments? Characterize detrital material
Fluorescence	chla, phyco	How much pigment, with extra caveats…
	Hydrocarbon	oil, crude vs. fine

Active vs. Passive Sensing

IOP sensors are active sensors

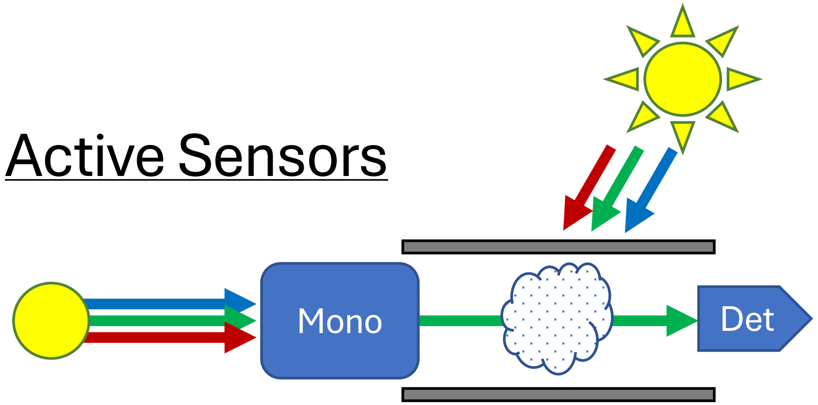
Radiometers are passive sensors

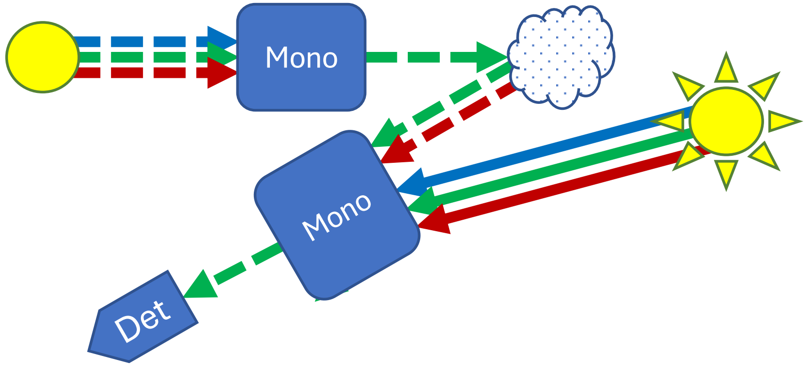
<u>Passive Sensors</u>



No modulation allows long and dynamic integration time

<u>Active Sensors</u>



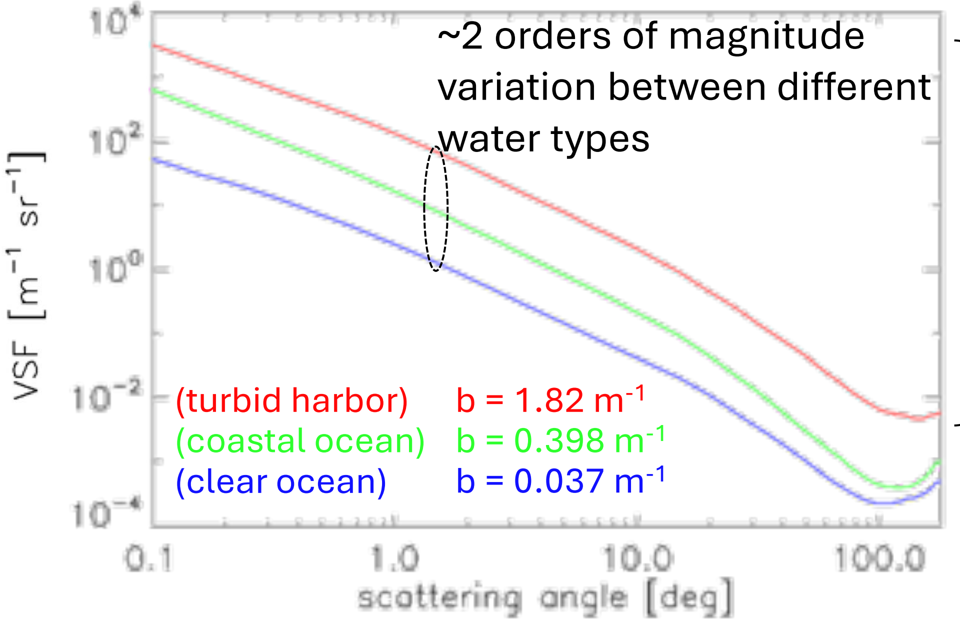


Source modulation needed for separation of ambient light, limiting detector integration time

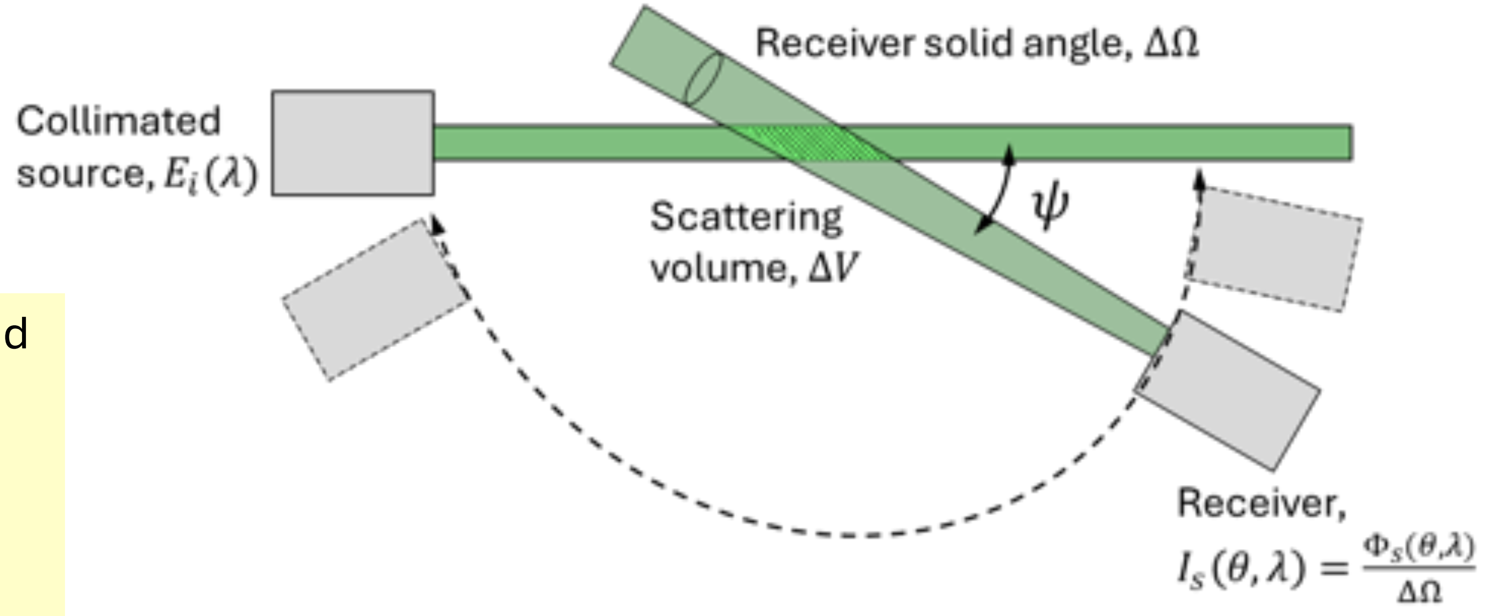
Measuring angular scattering

$$\beta(\psi,\lambda) = \frac{dI(\psi,\lambda)}{E_i(\lambda)\, dV} \approx \frac{\Phi_S(\psi,\lambda)}{E_i(\lambda)\, \Delta V(\psi)\, \Delta\Omega}$$

$$\left[\frac{(\mathrm{W})}{(\mathrm{W\ m^{-2}})(\mathrm{m^3})(\mathrm{sr})} = \mathrm{m^{-1}\ sr^{-1}}\right]$$



>6 orders of magnitude variation across scattering angles for a given VSF



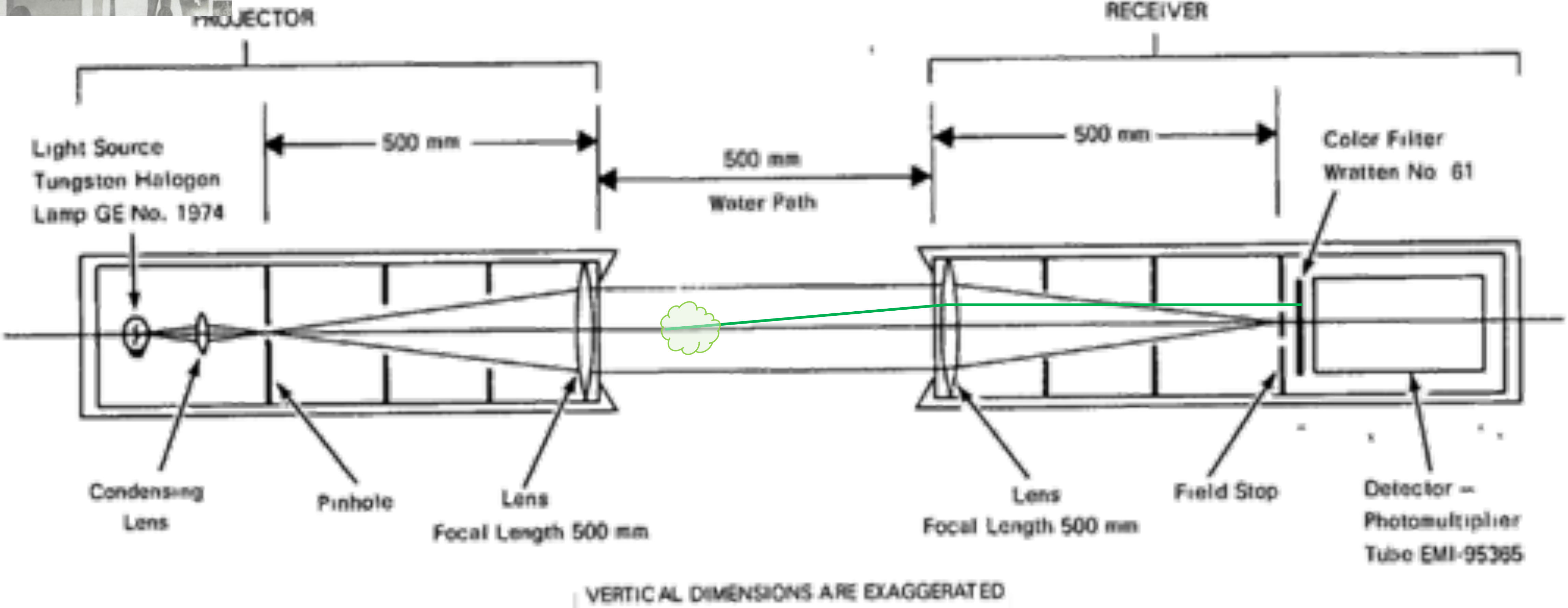
Difficulties with this method for near-forward and near-backward angles and need to characterize the scattering volume

Design trade-offs between angle range, resolution, SNR, dynamic range, time for a scan

Near-forward scattering measurement with LASM

Collimated source (broadband lamp)

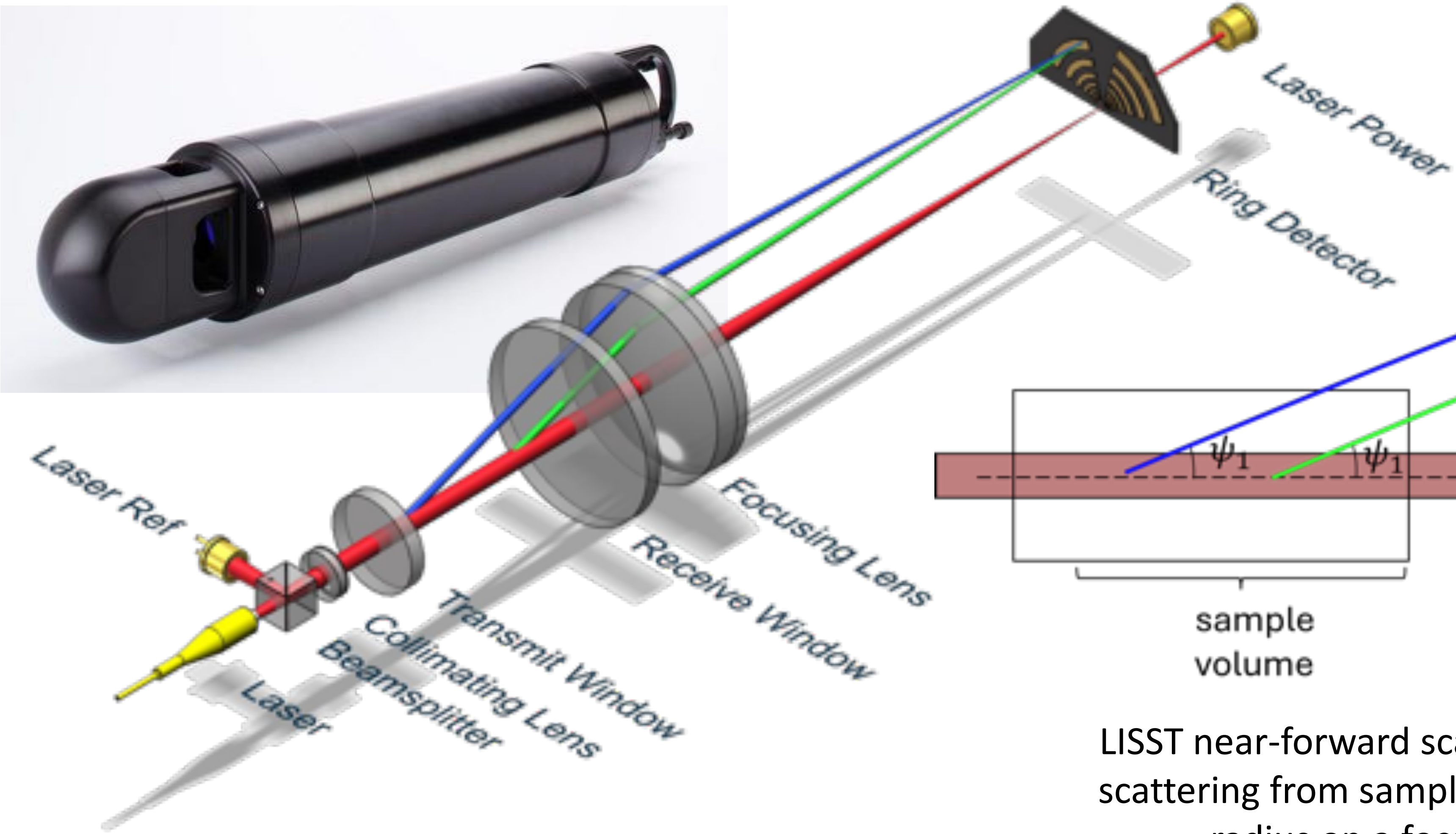
Scattering imaged through lens onto field stop – pinhole for transmission, annuluses for angles <5°

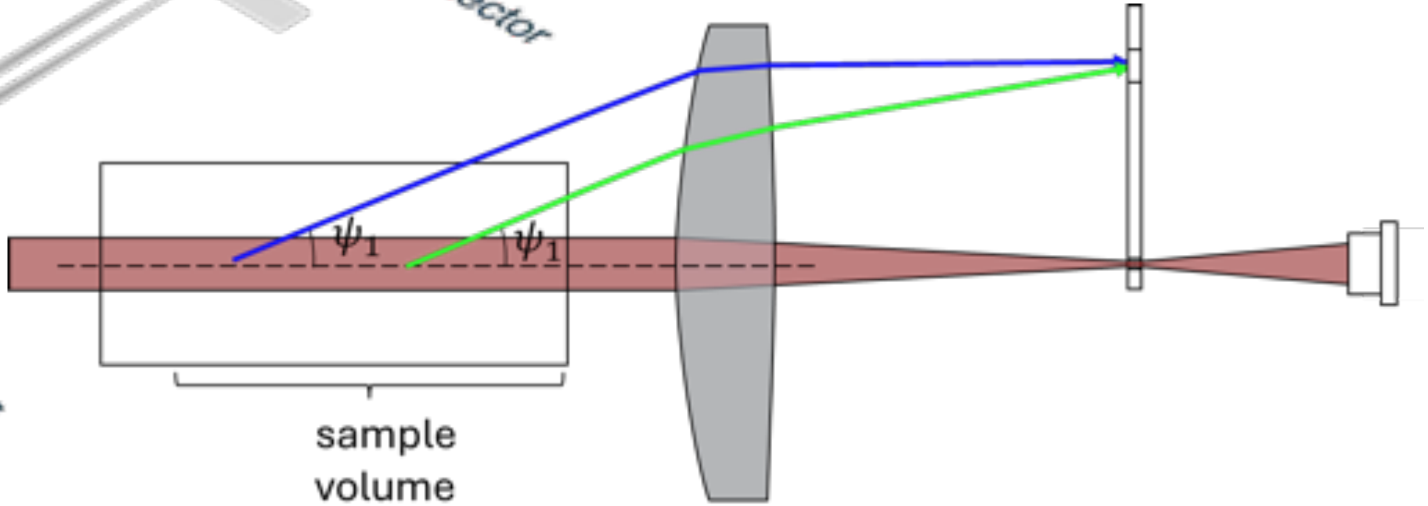


Petzold (1972) "Volume Scattering Functions for Selected Ocean Waters"

Near-forward scattering measurement with LISST

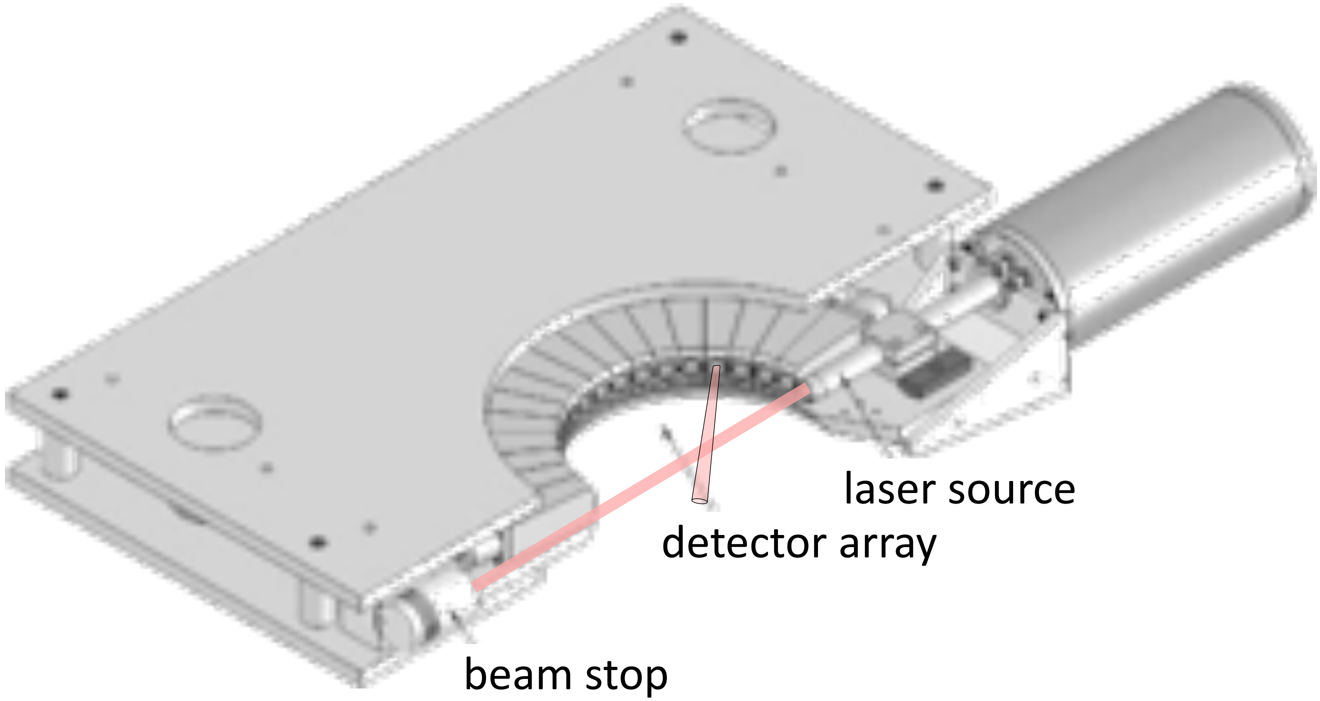
Transmissometer: laser source with reference detector and transmitted power detector (very small acceptance angle)





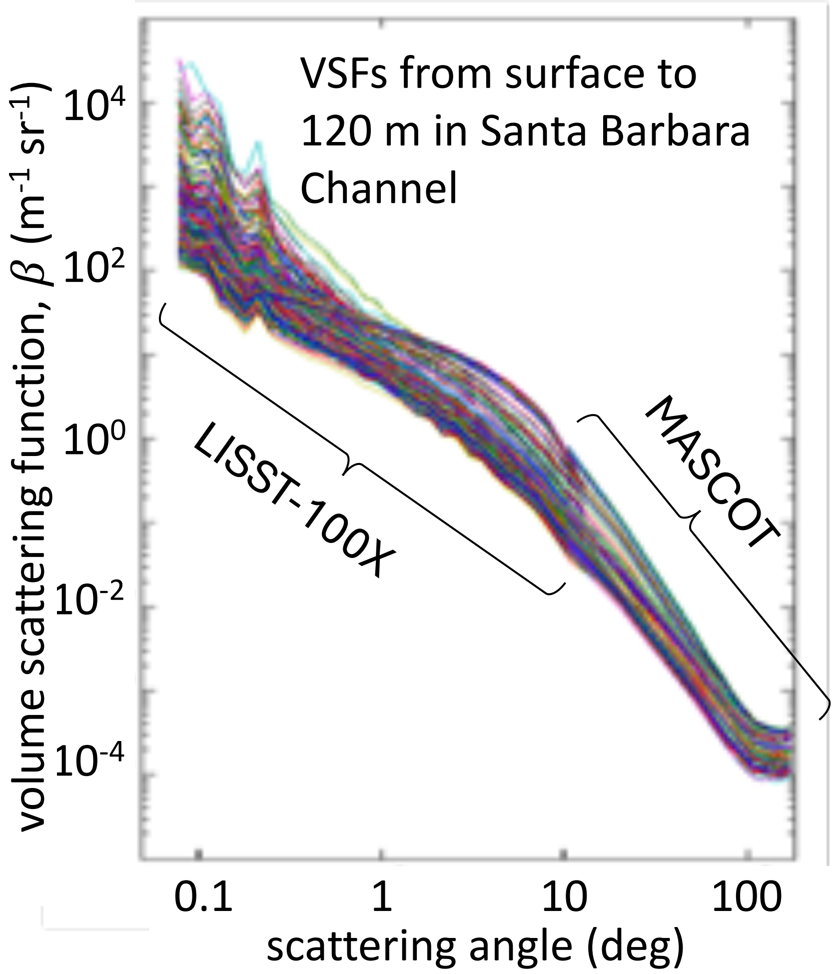
LISST near-forward scattering uses a Fourier lens to direct scattering from sample volume at a given angle to a given radius on a focal plane detector ($r = f \sin\theta$)

MASCOT scattering sensor



<u>MASCOT</u>
Fixed detectors
10 to 170 deg
10 deg increments
(can include polarization)

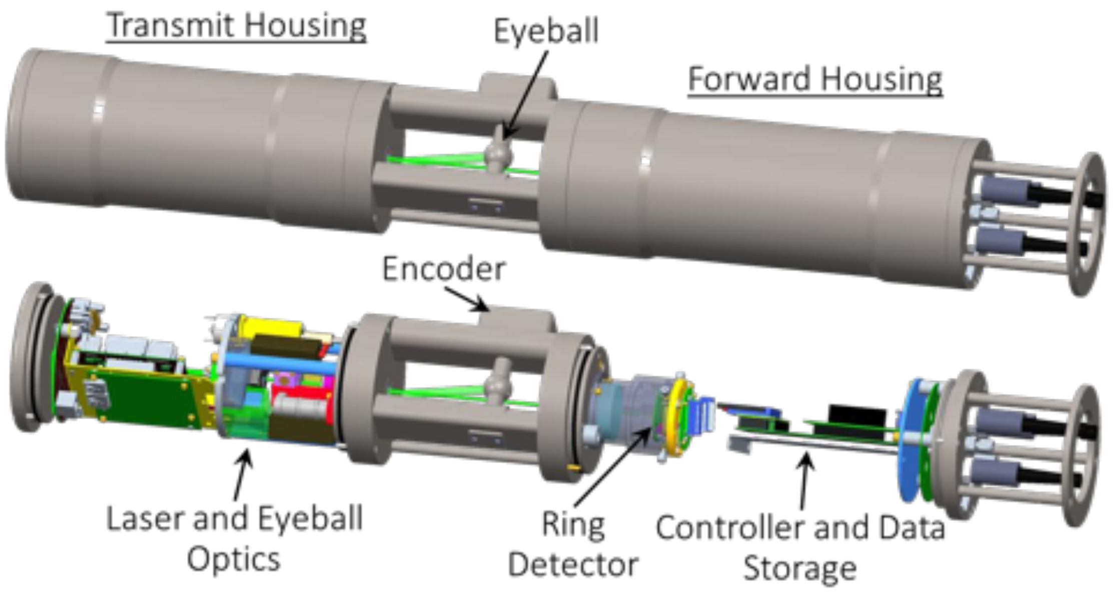
<u>Sequoia Type-B LISST</u>
0.01 to 12.9 deg
32 log-space increments



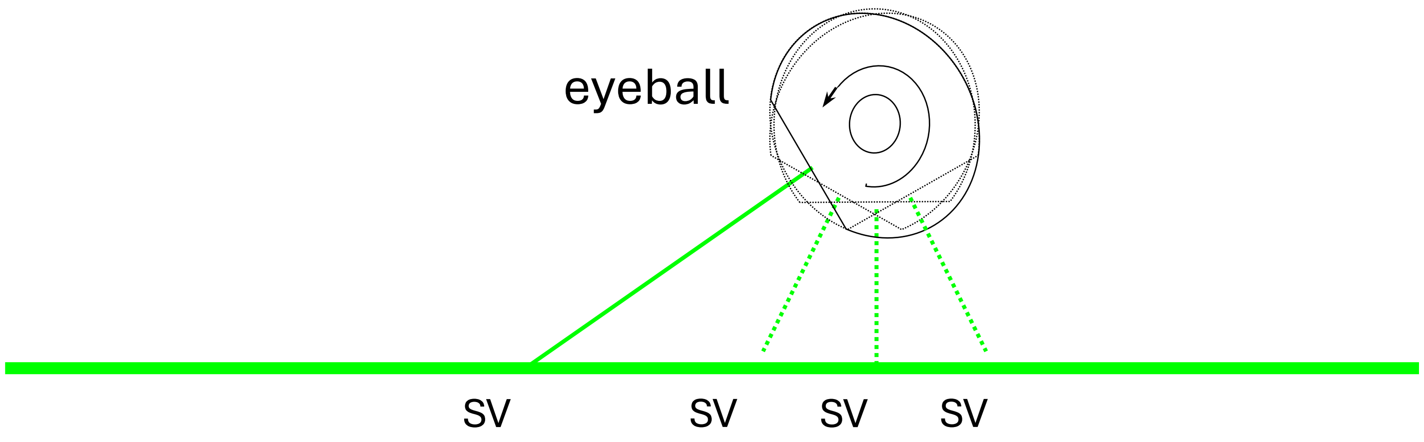
Sullivan and Twardowski (2009) doi:10.1364/AO.48.006811

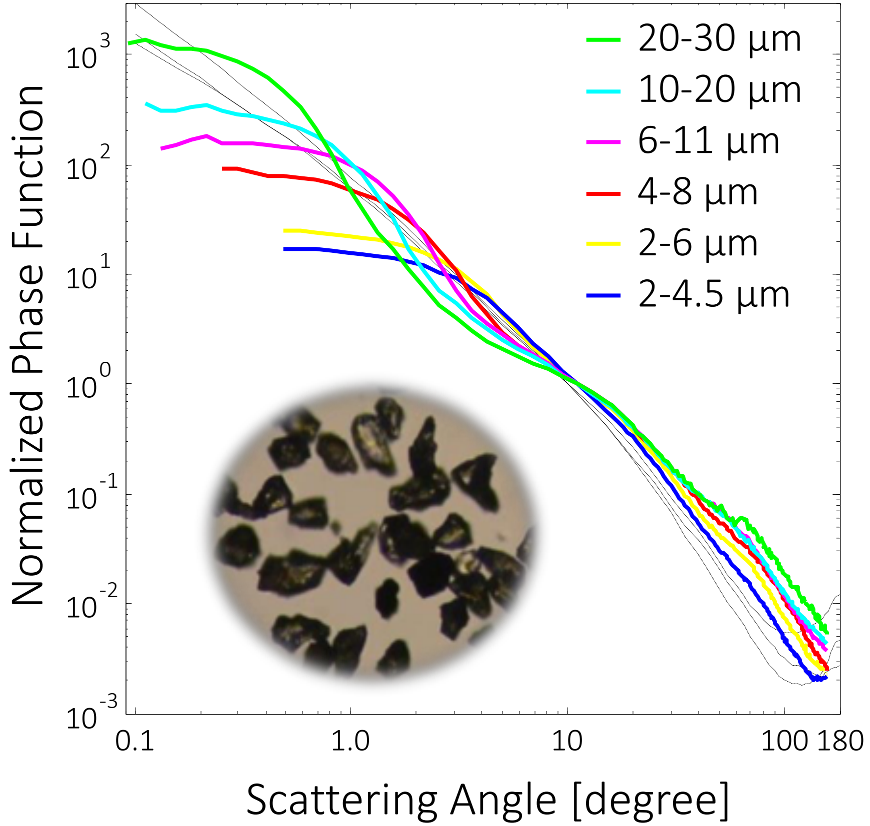
Figure/data from M. Twardowski

LISST-VSF scattering and polarization instrument



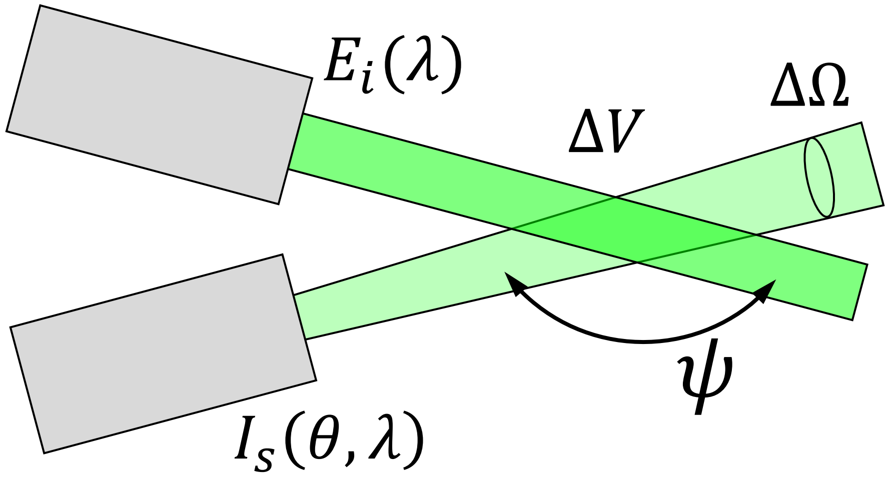
Eyeball scans VSF from approx. 10 to 160°, LISST-type near-forward scattering optics measures VSF from approx. 0.1 to 15°, and the two are merged during processing



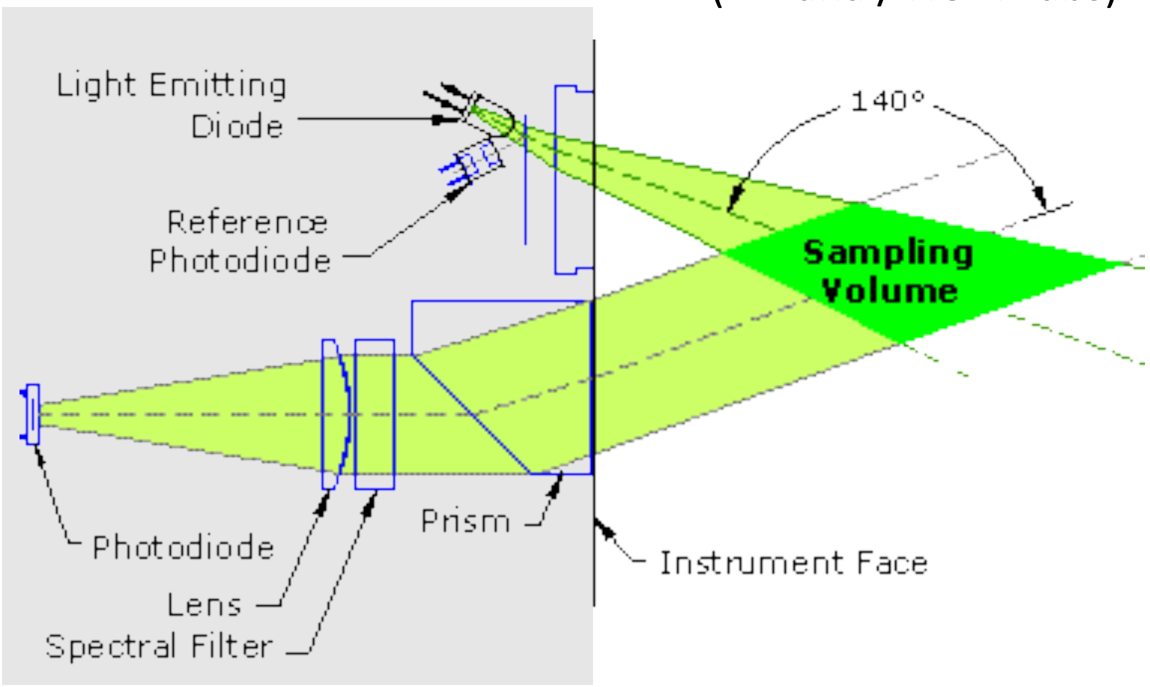


Slade et al. (2013)

Measuring VSF at an angle in the backwards direction



HydroScat optics
(D Dana / HOBI Labs)



Sequoia Scientific
Hyper-bb

Building Ocean Optics Sensors

Some common themes in design

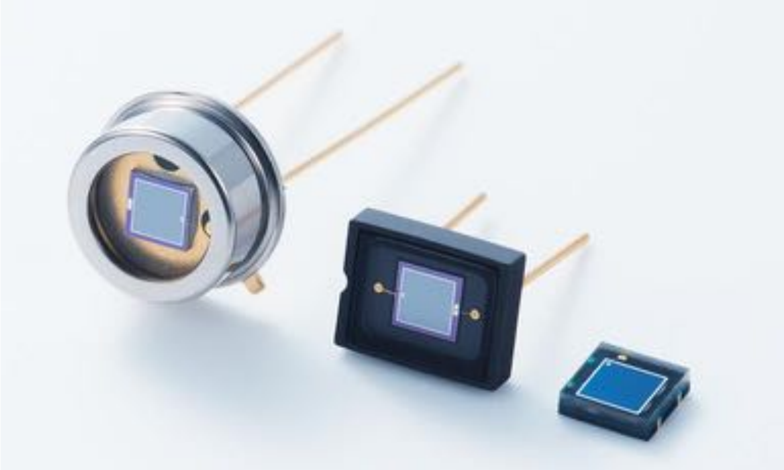
Quantifying Optical Power	Photodiodes Photomultiplier tubes CCD/CMOS arrays	Calibration: watt/amp watt/count	Active sensors can use reference detector
Light Sources	Broadband	Conventional lamps (vis-IR) Xenon lamps, UV lamps Broadband (white) LEDs	
	Narrowband	LEDs Lasers	UV to IR Spectral options vary
Spectral Separation	Monochromator Spectrometer	Bandpass filters Gratings Prisms	Linear variable filters Reflective, concave, transmissive
	Dichroics	Long- or short-pass	

Building Ocean Optics Sensors

Some common themes in design

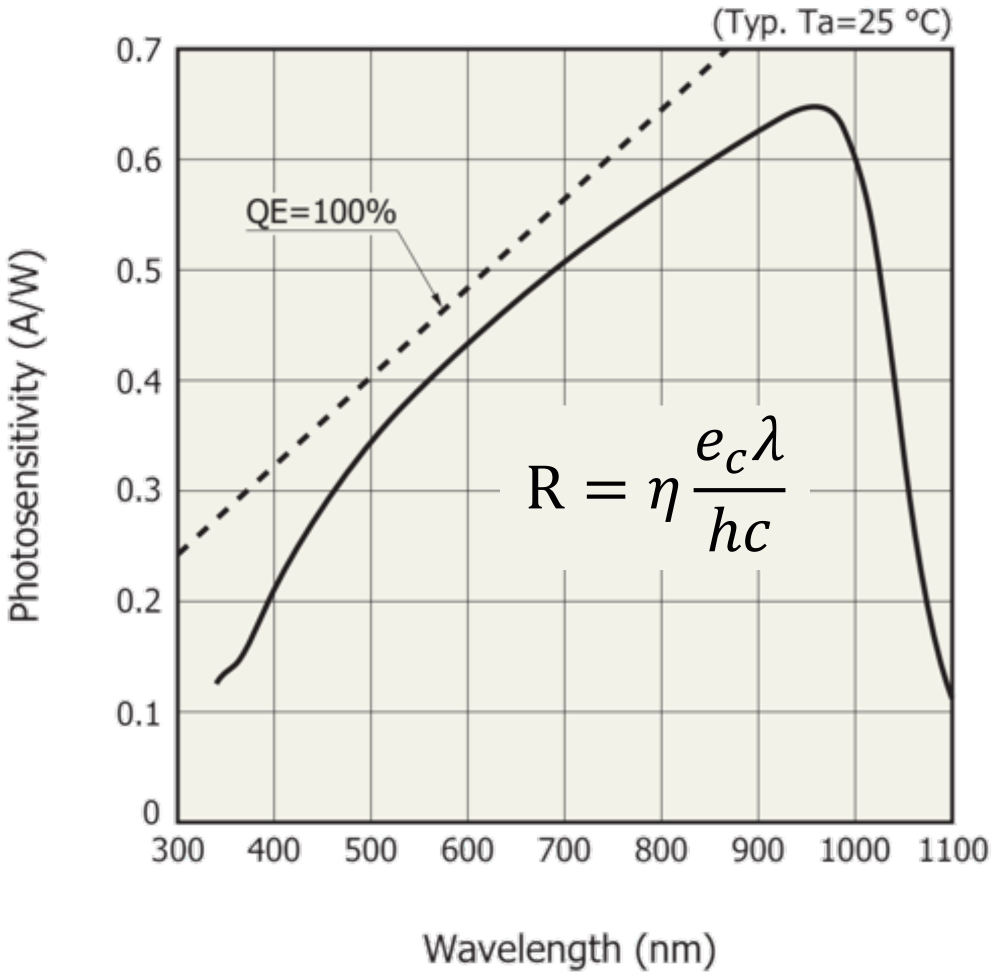
Spectral Bands	Broadband / undefined Single wavelength band Multiple wavelength bands	Design with bandpass Multi-spectral Hyperspectral	
Optical Elements	Lenses Beamsplitter Cube/Plate	Polarizers Diffusers	
Collimating	Creating “light beam” from source	Limiting FOV in detectors	Use lens or concave mirror
Ambient Light Rejection	Modulation of source (on-off) to subtract ambient		

Photodiodes are the most common detectors in ocean optical instruments



Semiconductor PIN-junction is similar to a normal diode, but constructed to allow light onto junction

Absorption of photon with sufficient energy generates electron-hole pair → photocurrent



$$R = \eta \frac{e_c \lambda}{hc}$$

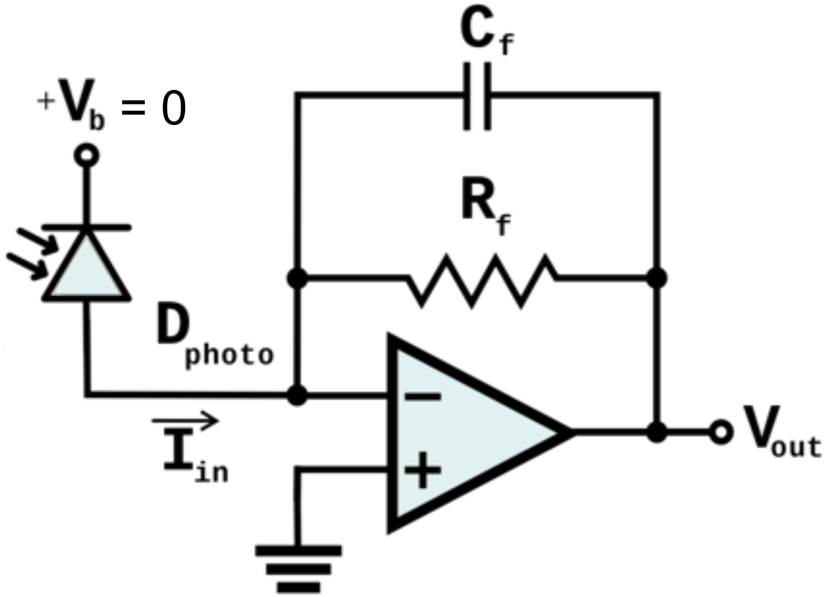
https://www.hamamatsu.com/us/en/product/optical-sensors/photodiodes/index.html

Photodiode Example

Transimpedance Amp =
current to voltage converter

Low impedance input for
photodiode current

Large gain set by Rf



$$V_{out} = -I_d R_f$$

Back of envelope: 1 nW power, ~500 nm, incident on PD. Responsivity at 500 nm is 0.35 A/W, so photocurrent generated is 0.35 nA. TIA has Rf = 1 MΩ, so Vout = -0.35 mV.

Typical next steps in system: additional gain, level shifting, digitization

How much light can PD receive before op-amp saturates? (dynamic range)

What happens to unwanted ambient light? How can you reduce unwanted light reaching your sensor?

https://en.wikipedia.org/wiki/Transimpedance_amplifier

Light Sources in Active Sensing

For active sensors, light sources can be major limitations

Trade-offs in spectral characteristics, power, collimation, stability

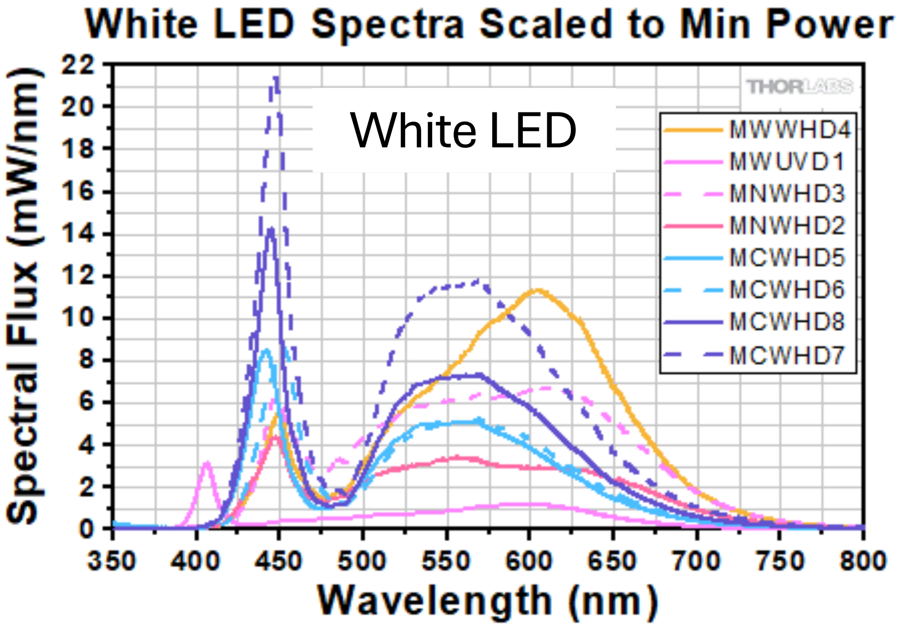
Broadband vs. narrowband sources

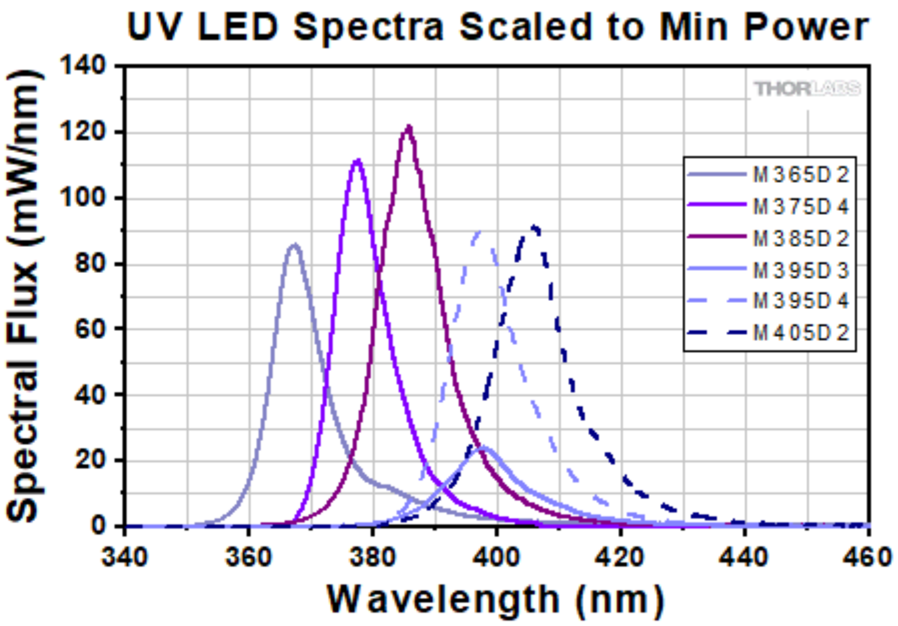
Common broadband sources:
Halogen, deuterium, xenon lamps
White LEDs

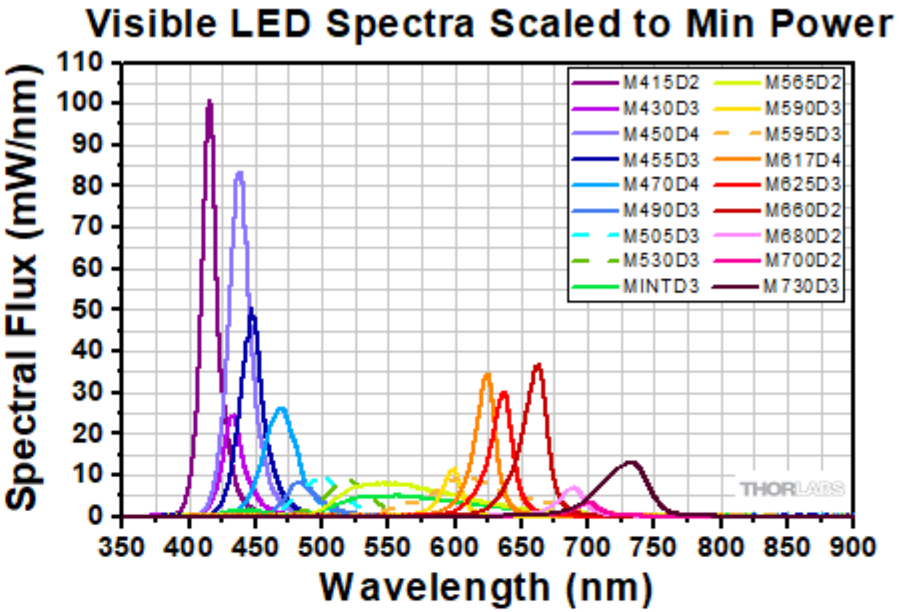
Common narrowband sources:
LEDs and lasers

Examples of LED sources

Advantages: simple, compact, long-life, modulation-capable, stable, high power, spectral bandpass



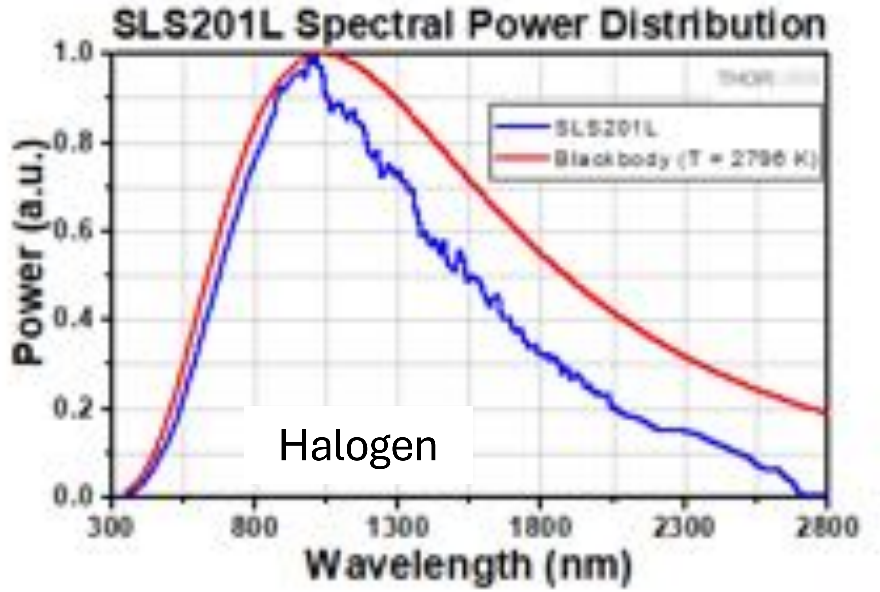


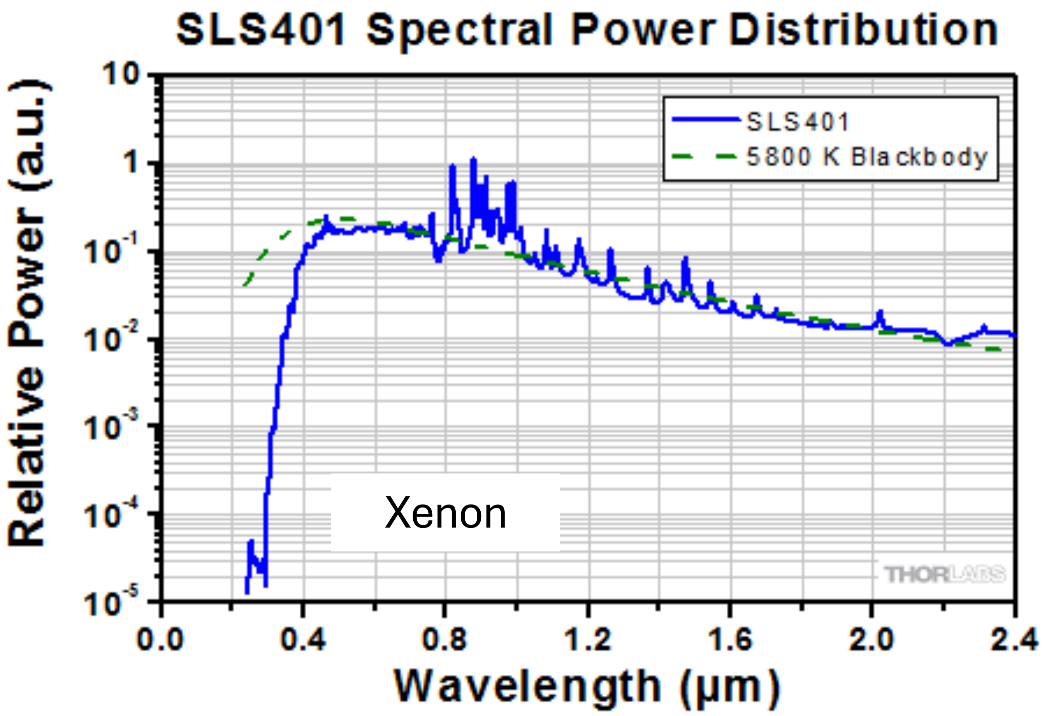


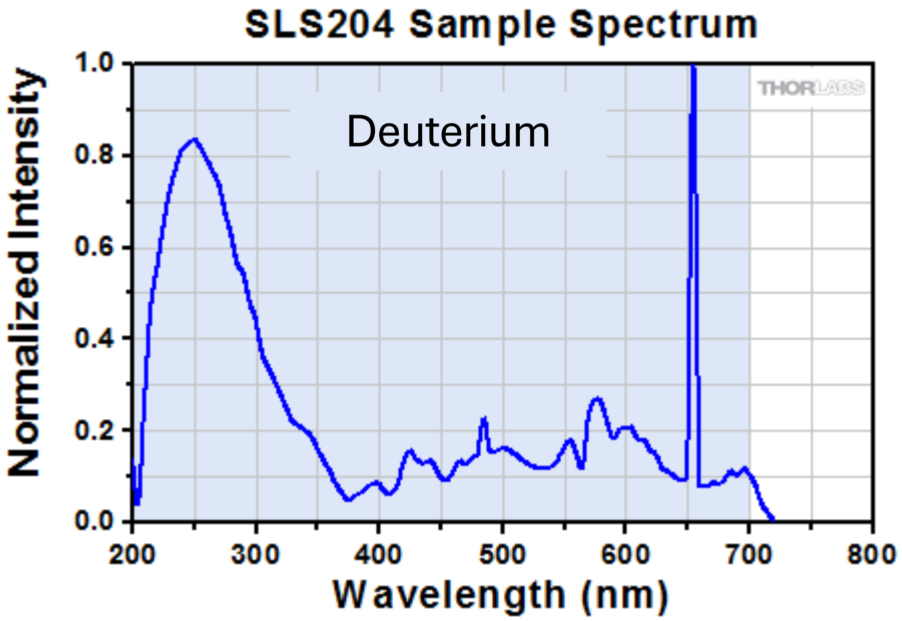
Disadvantages: large emitting area can make collimation difficult/inefficient, not truly broadband

https://www.thorlabs.com/navigation.cfm?guide_id=33

Examples of lamp sources







Advantages: simple (halogen), high power, broadband

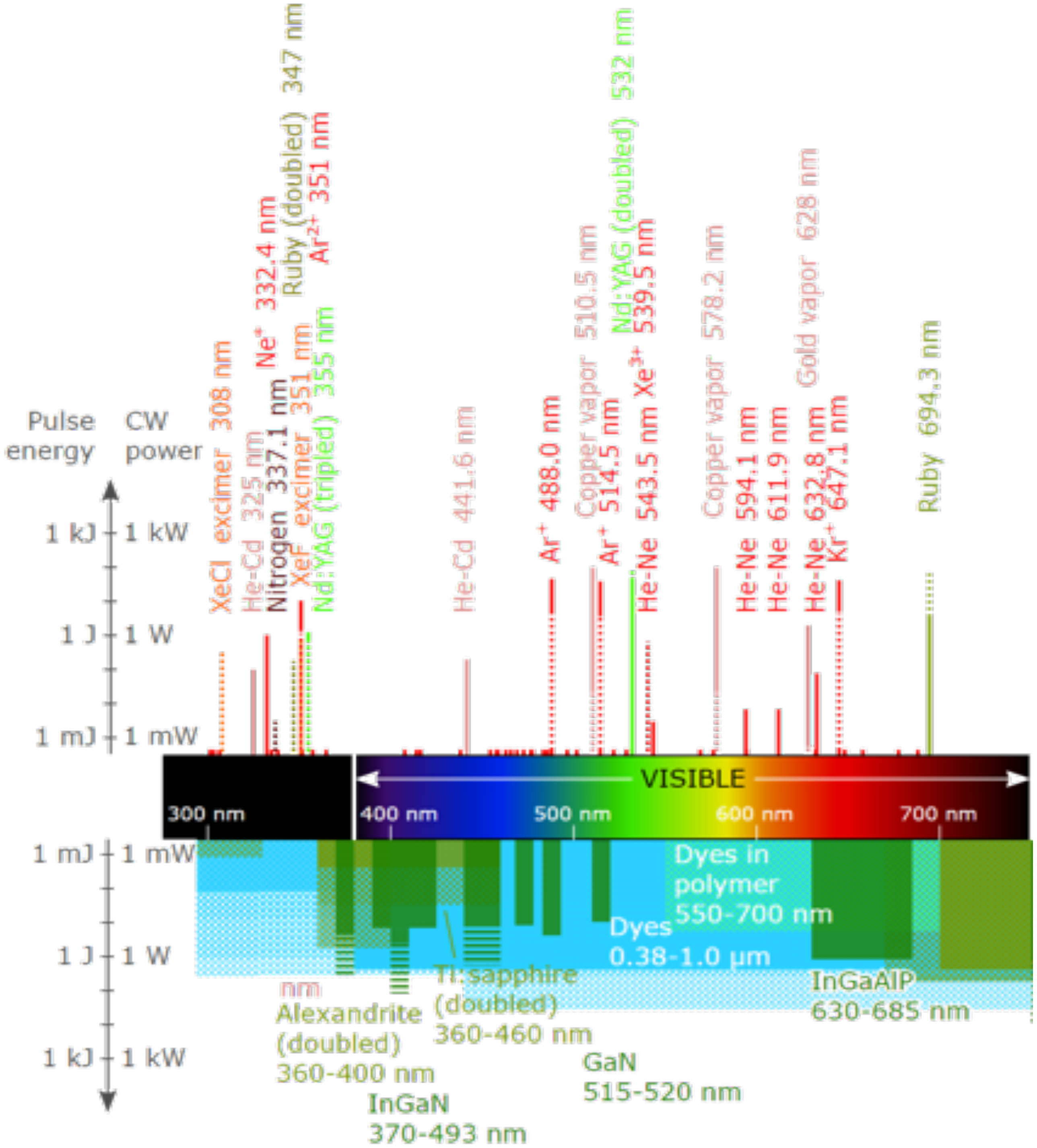
Disadvantages: shorter lifetime, inefficient and hot, difficult drive electronics (xenon)

https://www.thorlabs.com/navigation.cfm?guide_id=33

Examples of laser sources

Lasers solve several source issues if you want a single wavelength

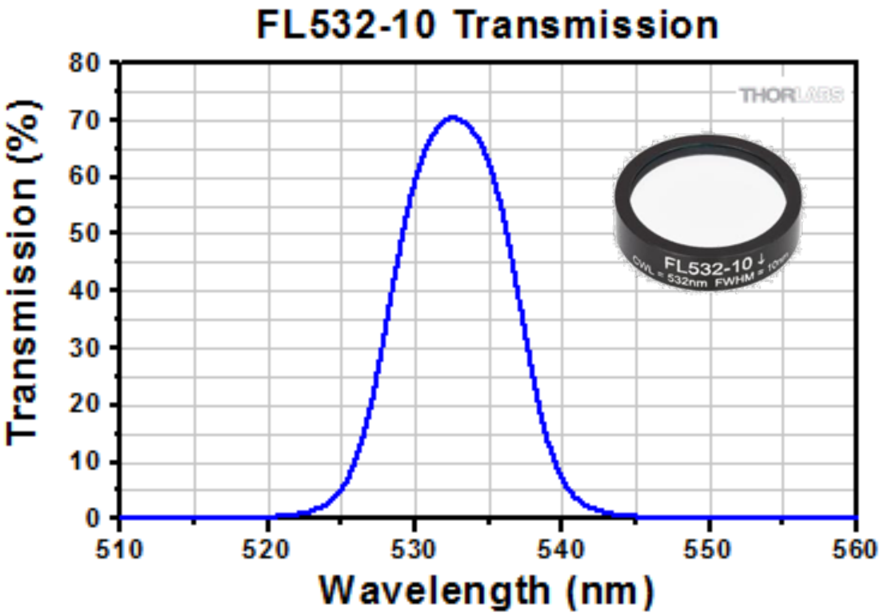
High efficiency and high power
Easily collimated
Pulsed or continuous options
Polarized



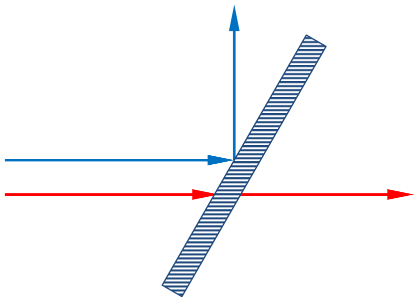
Adapted from https://en.wikipedia.org/wiki/List_of_laser_types

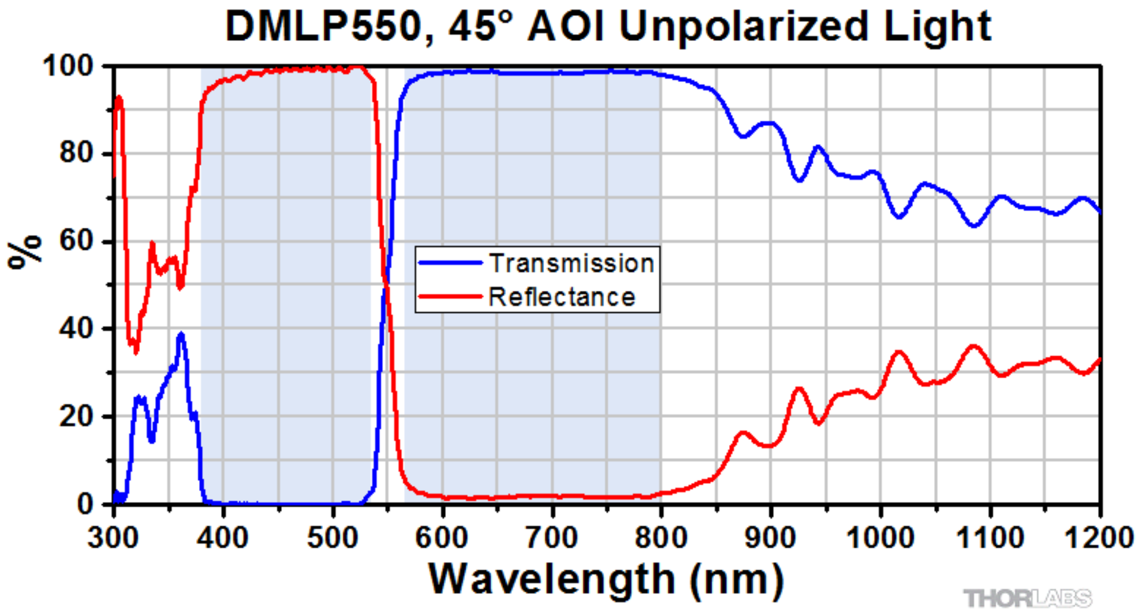
How to combine or separate spectral energy?

Bandpass
Filter



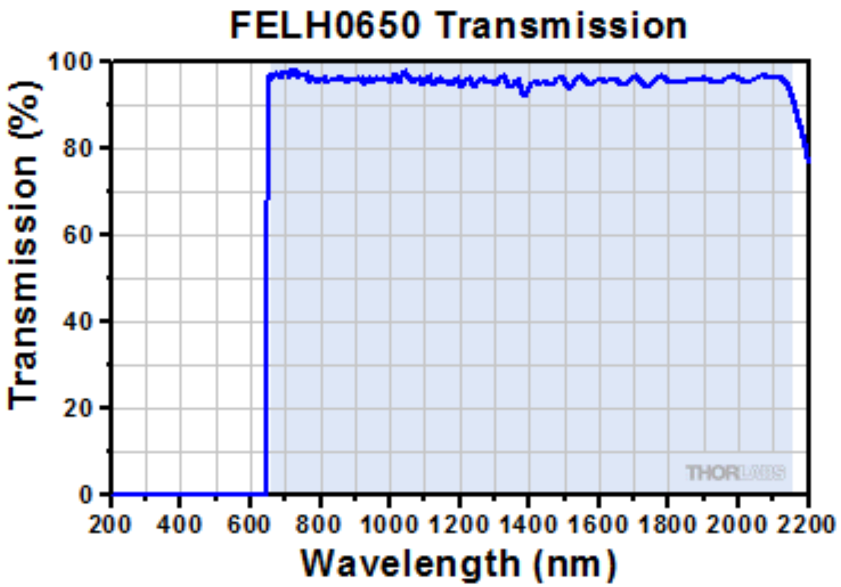
Dichroic
Mirror



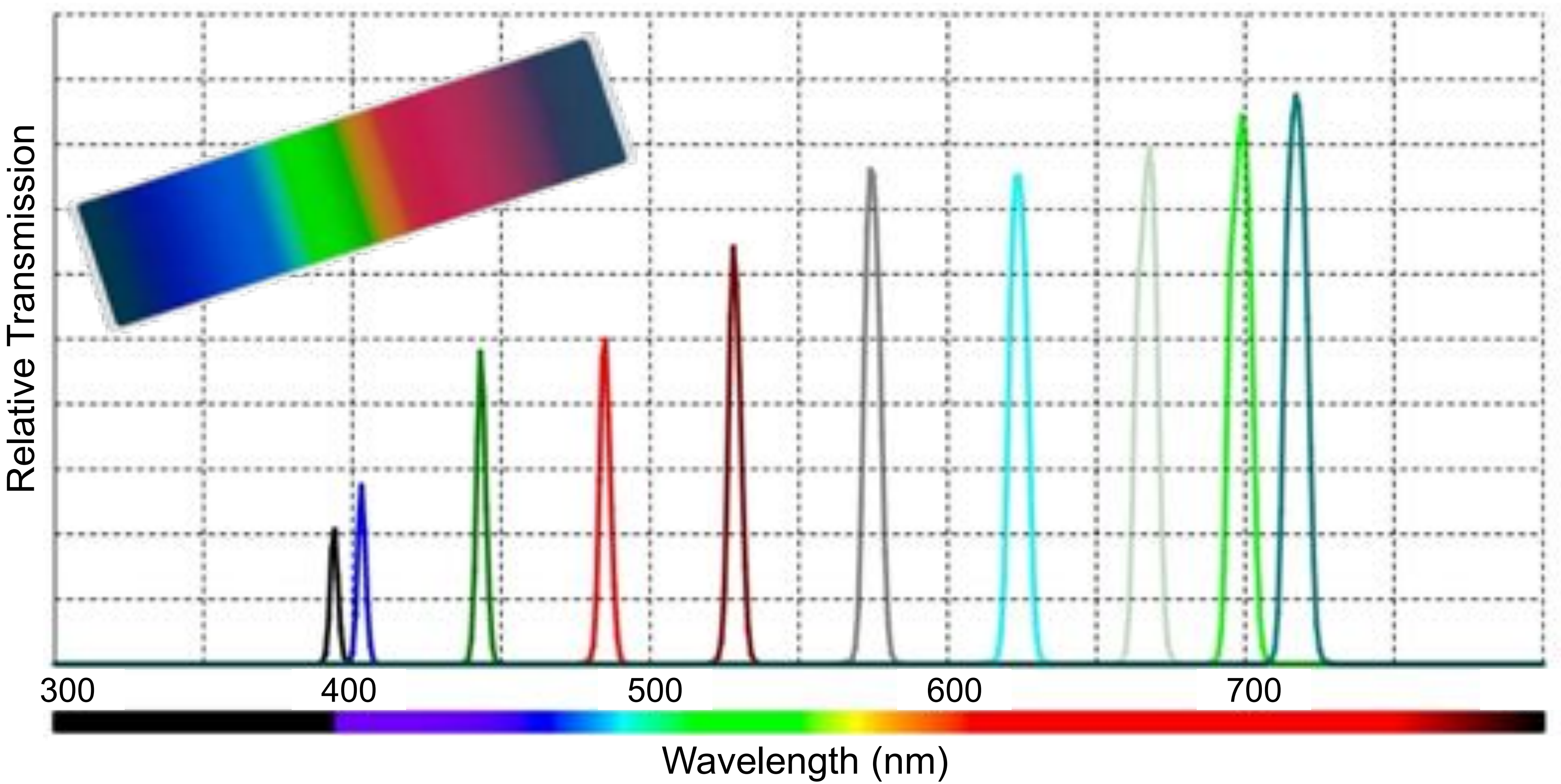


also
“Edgepass”

Longpass
Shortpass

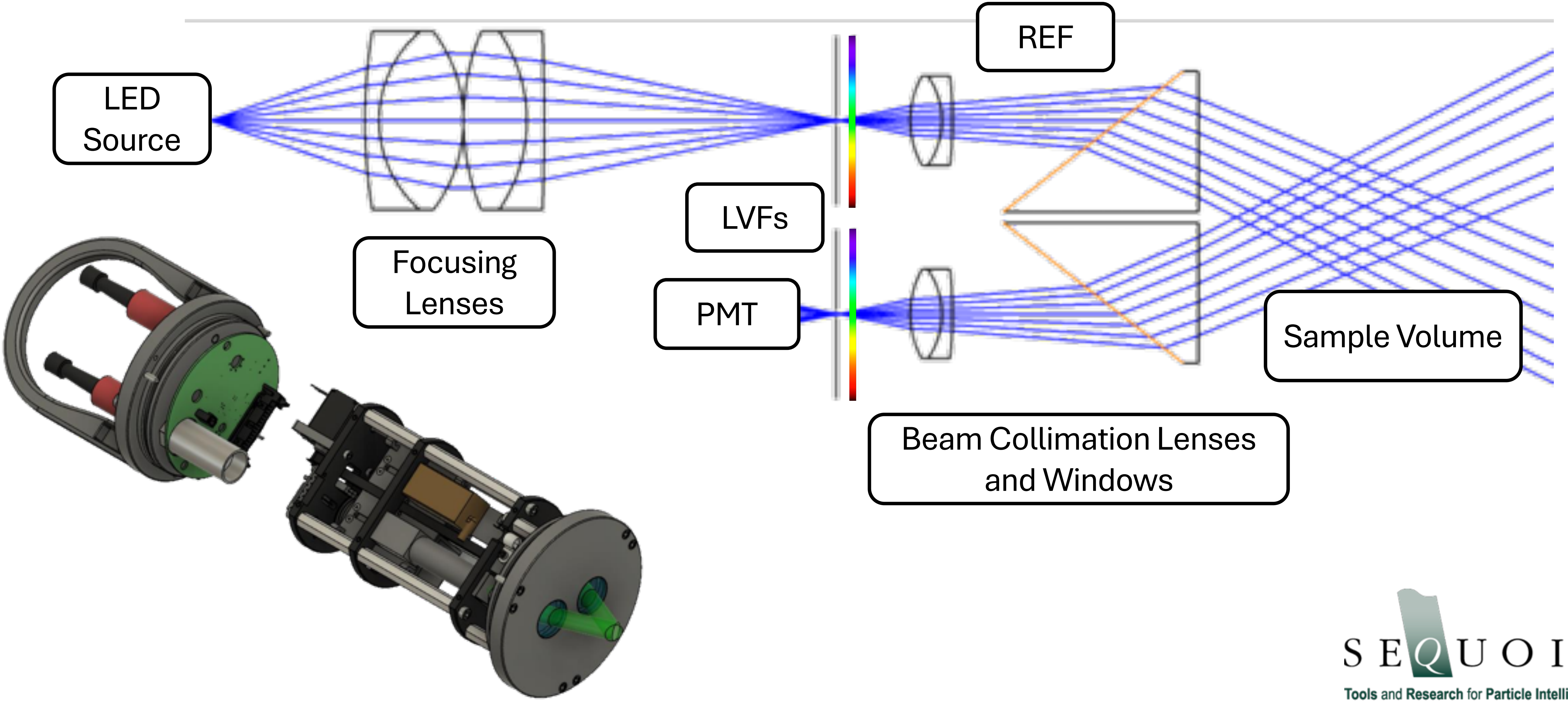


Linear variable bandpass (or edgepass) filters



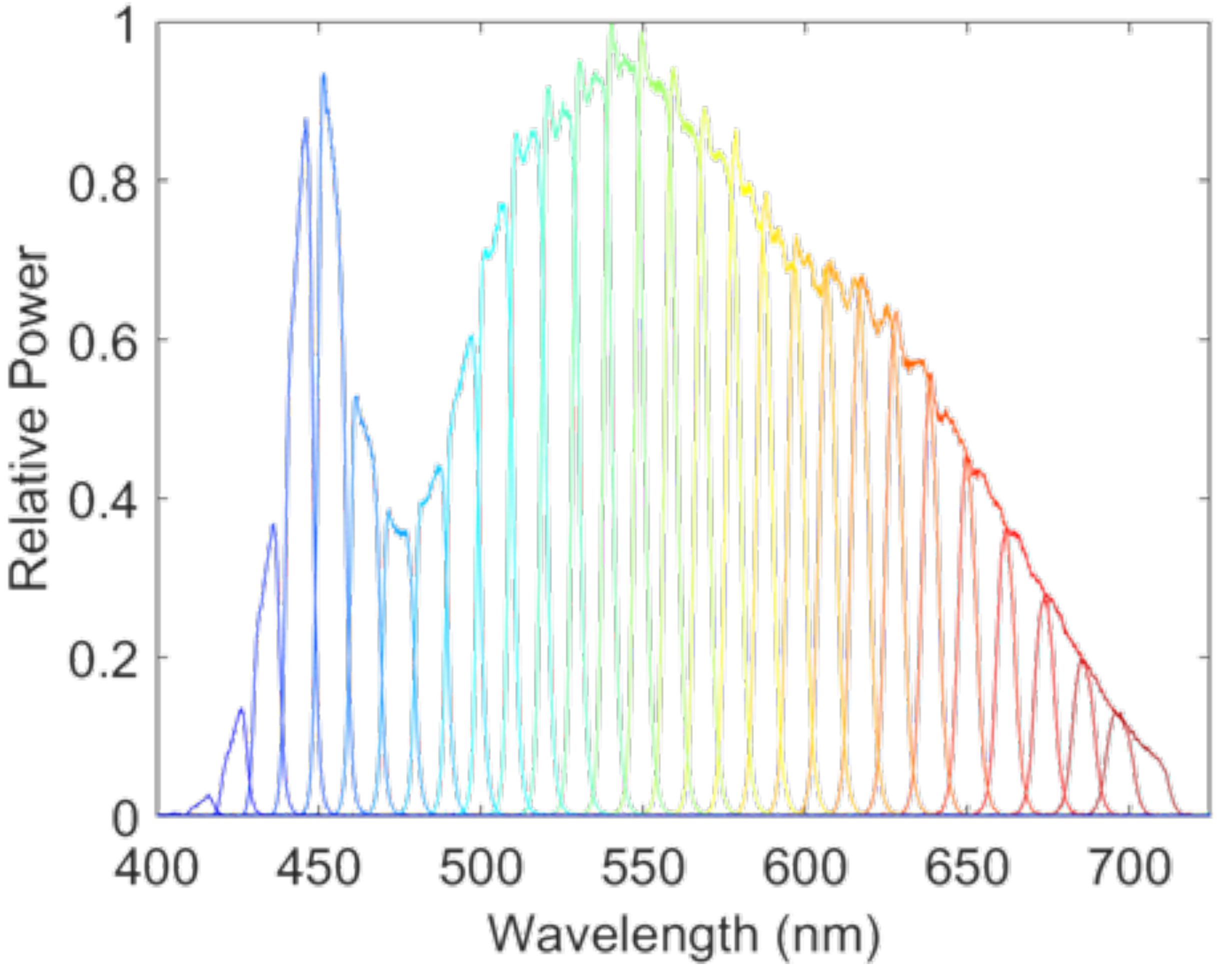
https://deltaopticalthinfilm.com/
wp-content/uploads/2022/11/LVVISBP-LF102773.pdf

Application of LVF – Sequoia Hyper-bb (and SeaBird ac-s)



SEQUOIA
Tools and Research for Particle Intelligence

Application of LVF – Sequoia Hyper-bb (and SeaBird ac-s)

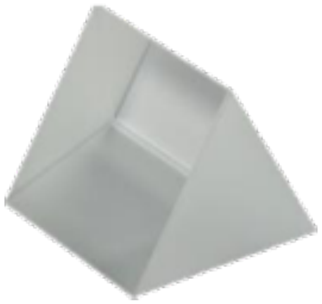


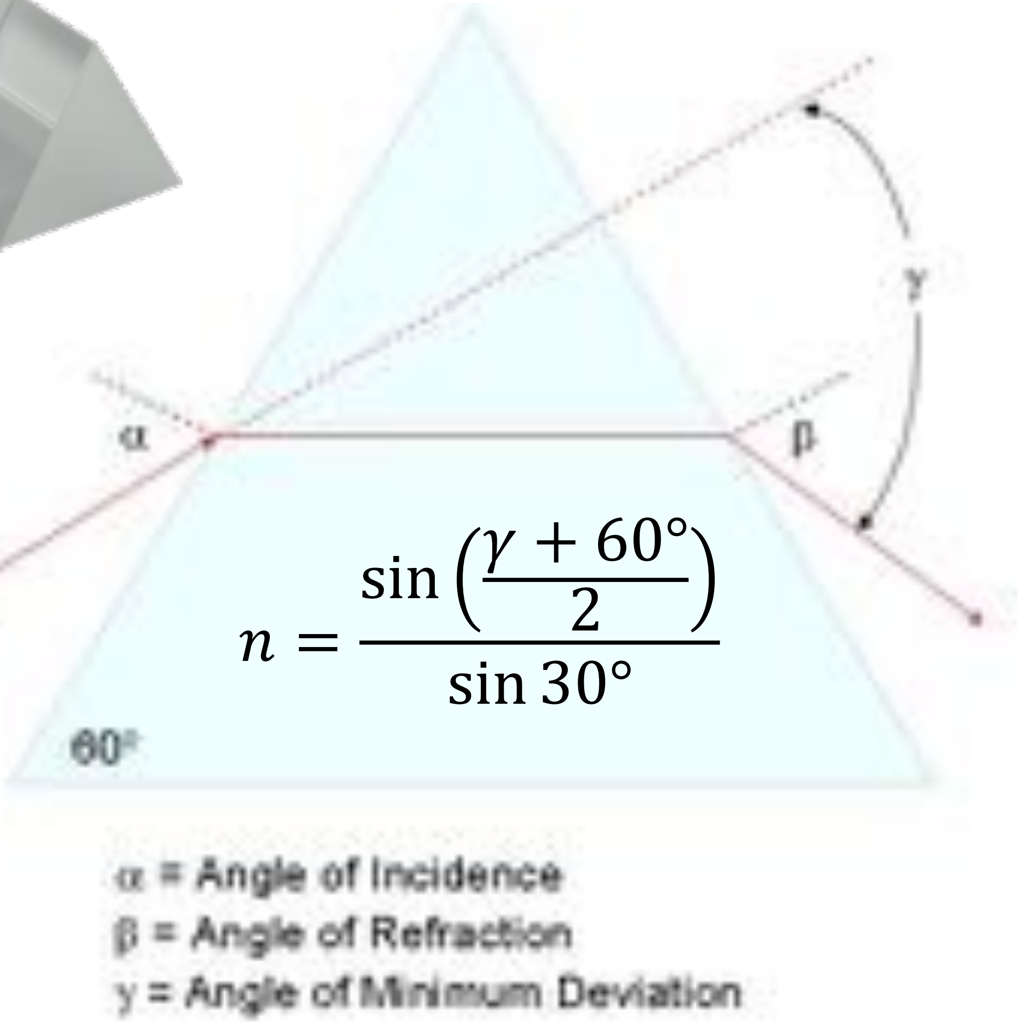
Hyperspectral measurement is configurable over ~430 to 700 nm, typ. application would be 430:10:700 nm channels, scan takes ~10-15 sec

Channel bandwidth is spectrally dependent (approx. 8 to 18 nm FWHM)

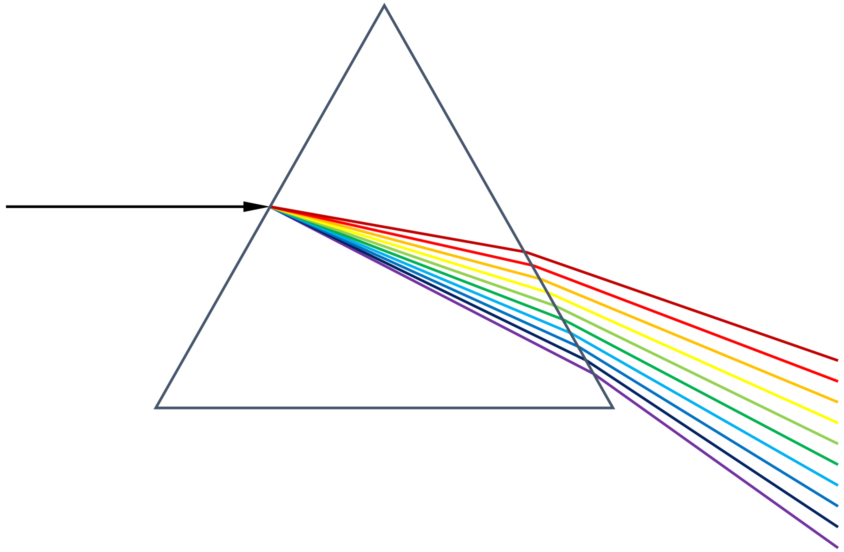
SEQUOIA
Tools and Research for Particle Intelligence

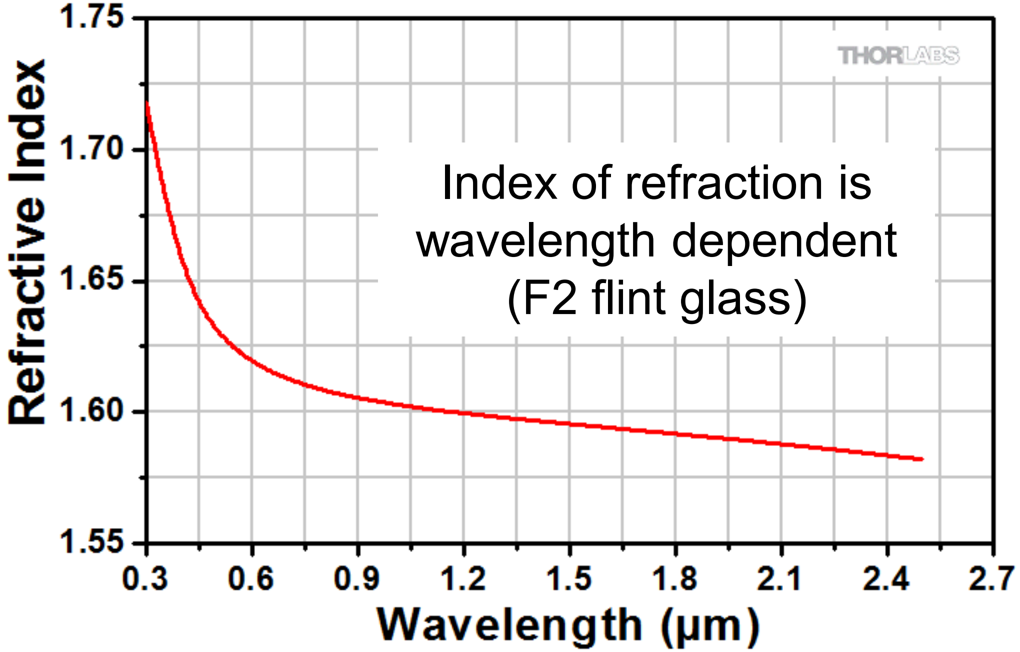
Dispersing prism for spectral separation





$$n = \frac{\sin\left(\frac{\gamma + 60°}{2}\right)}{\sin 30°}$$

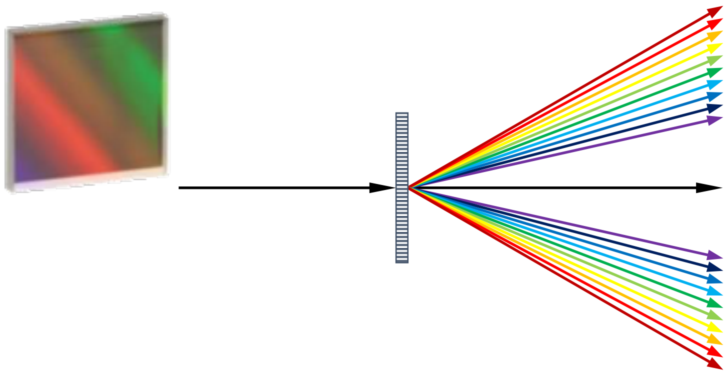


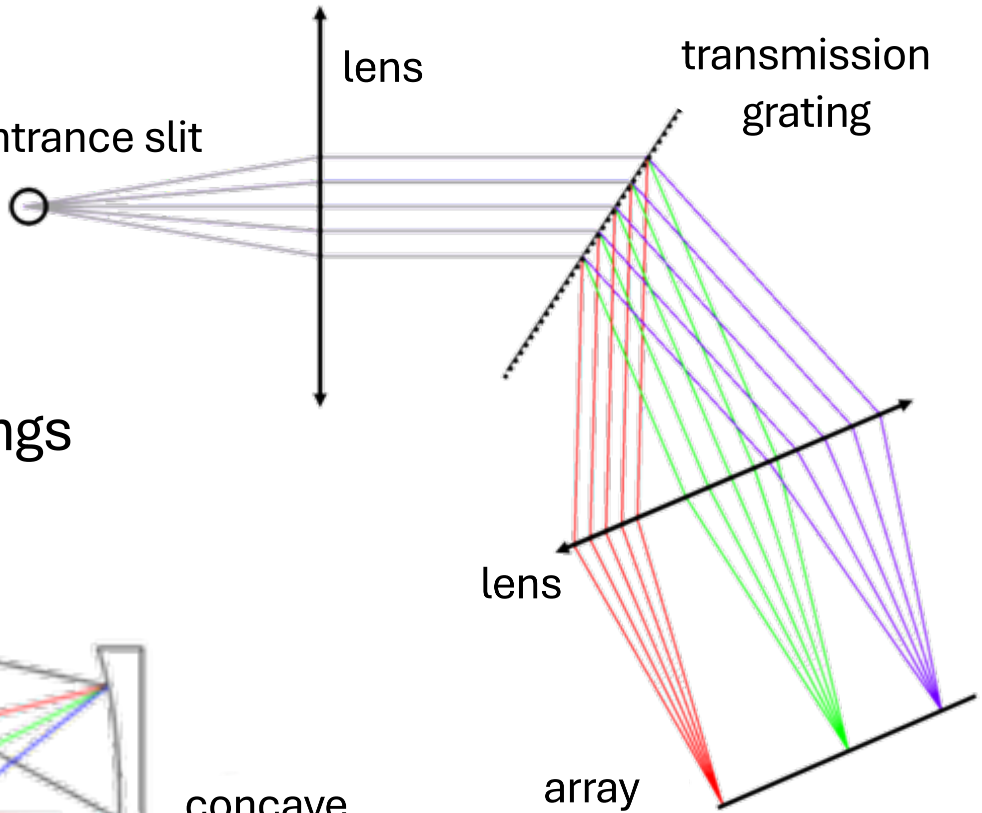


https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=148

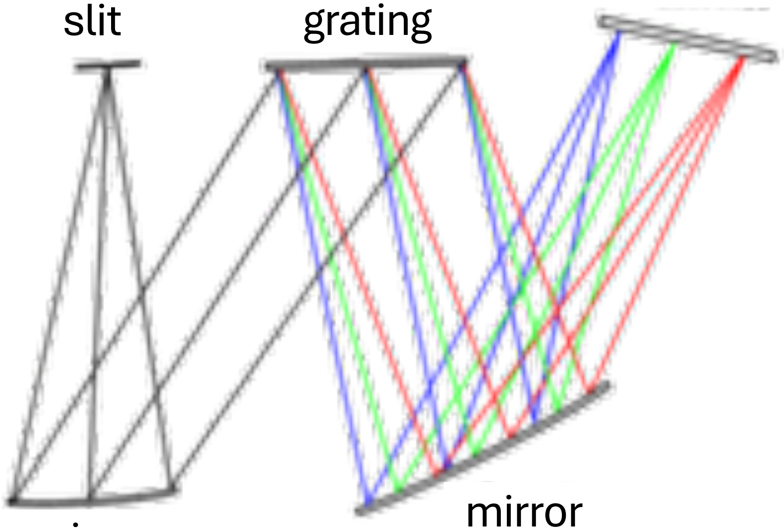
Spectrometer: diffraction grating for spectral separation

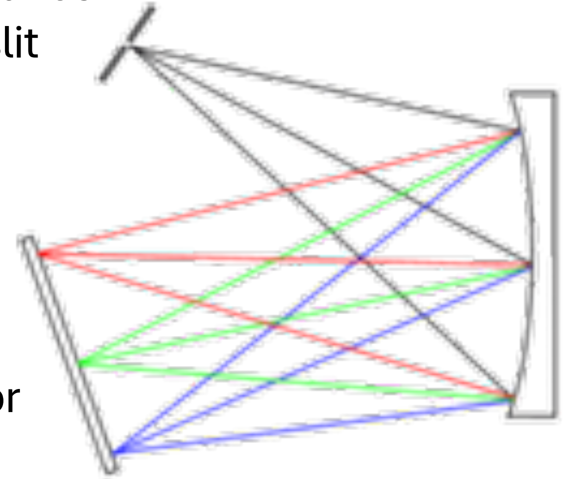
(stationary optics approaches)





Reflective vs. transmissive gratings





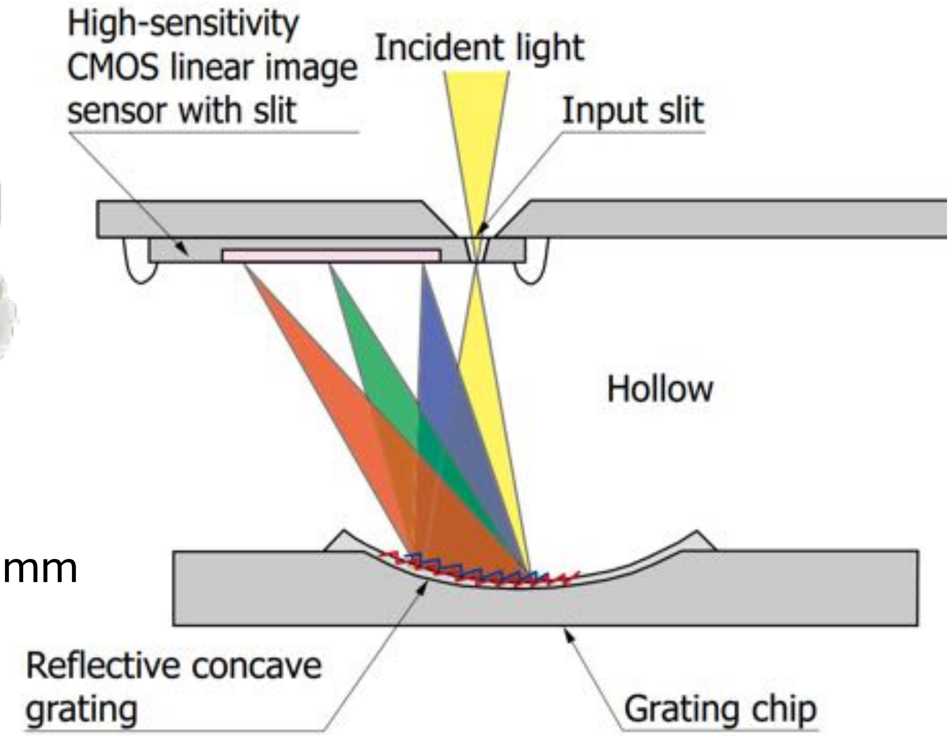
https://www.azom.com/article.aspx?ArticleID=13367

https://support.zemax.com/hc/en-us/articles/1500005578762-How-to-build-a-spectrometer-theory

Examples of “Lego”-style spectrometers for instrumentation

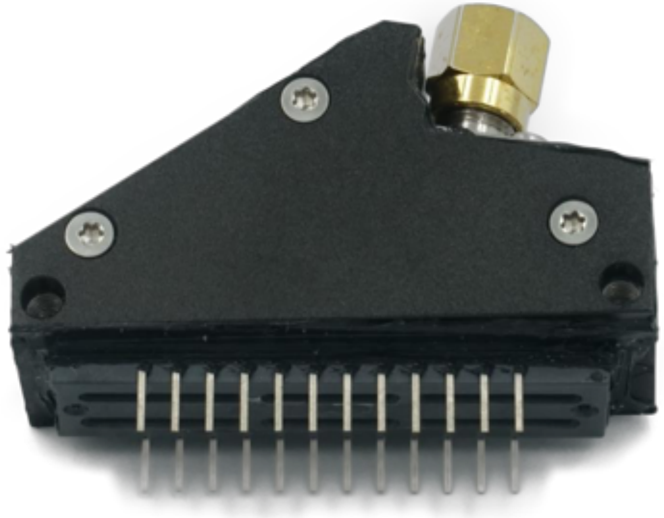
Mini-spectrometer C12880MA

Fingertip size:
20.1 × 12.5 × 10.1 mm



Spectral response range: 340 to 850 nm
Spectral resolution: 15 nm max.

FREEDOM UV-VIS



Footprint:
48 mm x 54 mm x 16 mm

Spectral response range: 190 to 850 nm
Configurable resolution: 1.7 nm to 11.4 nm

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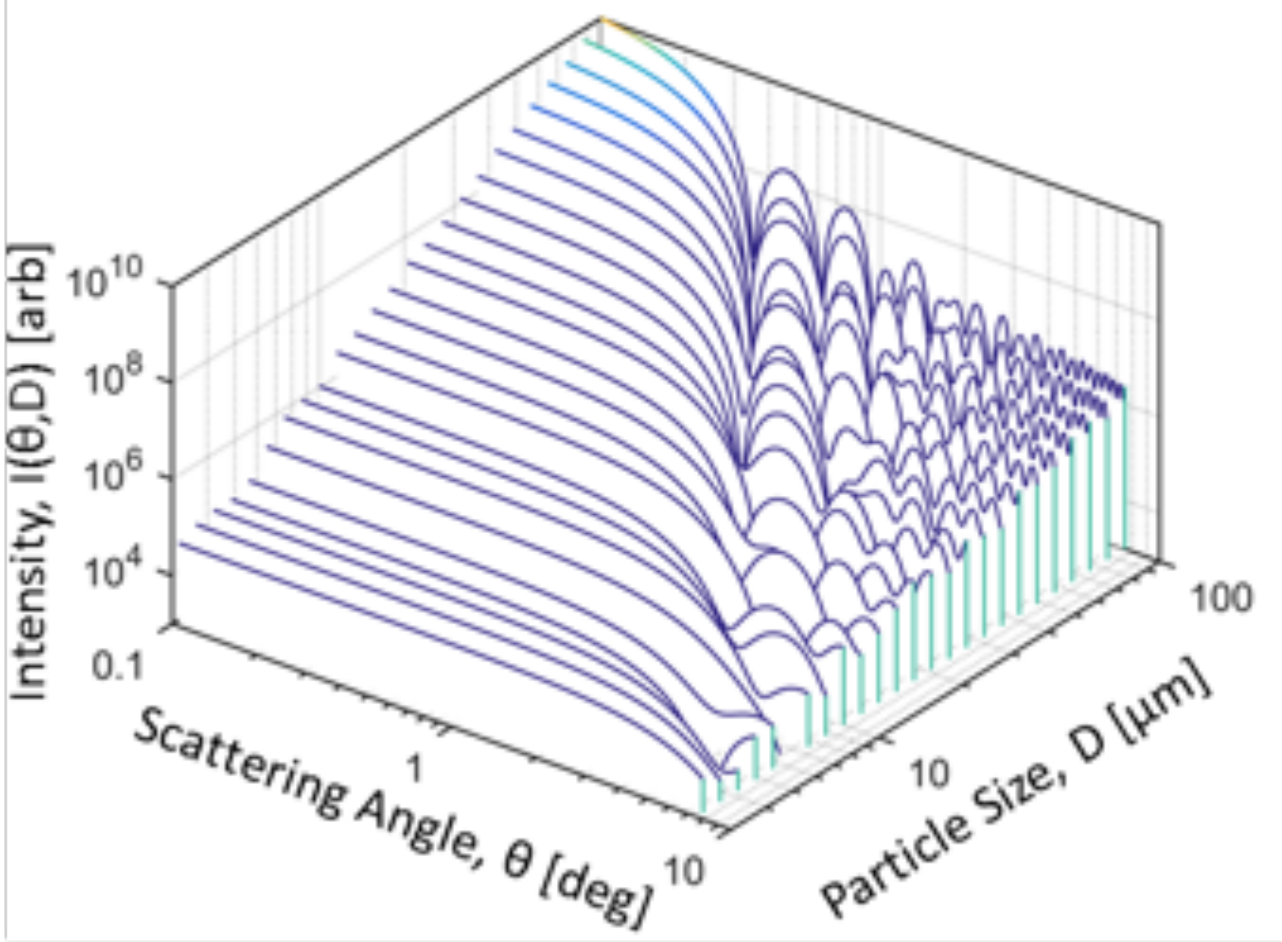
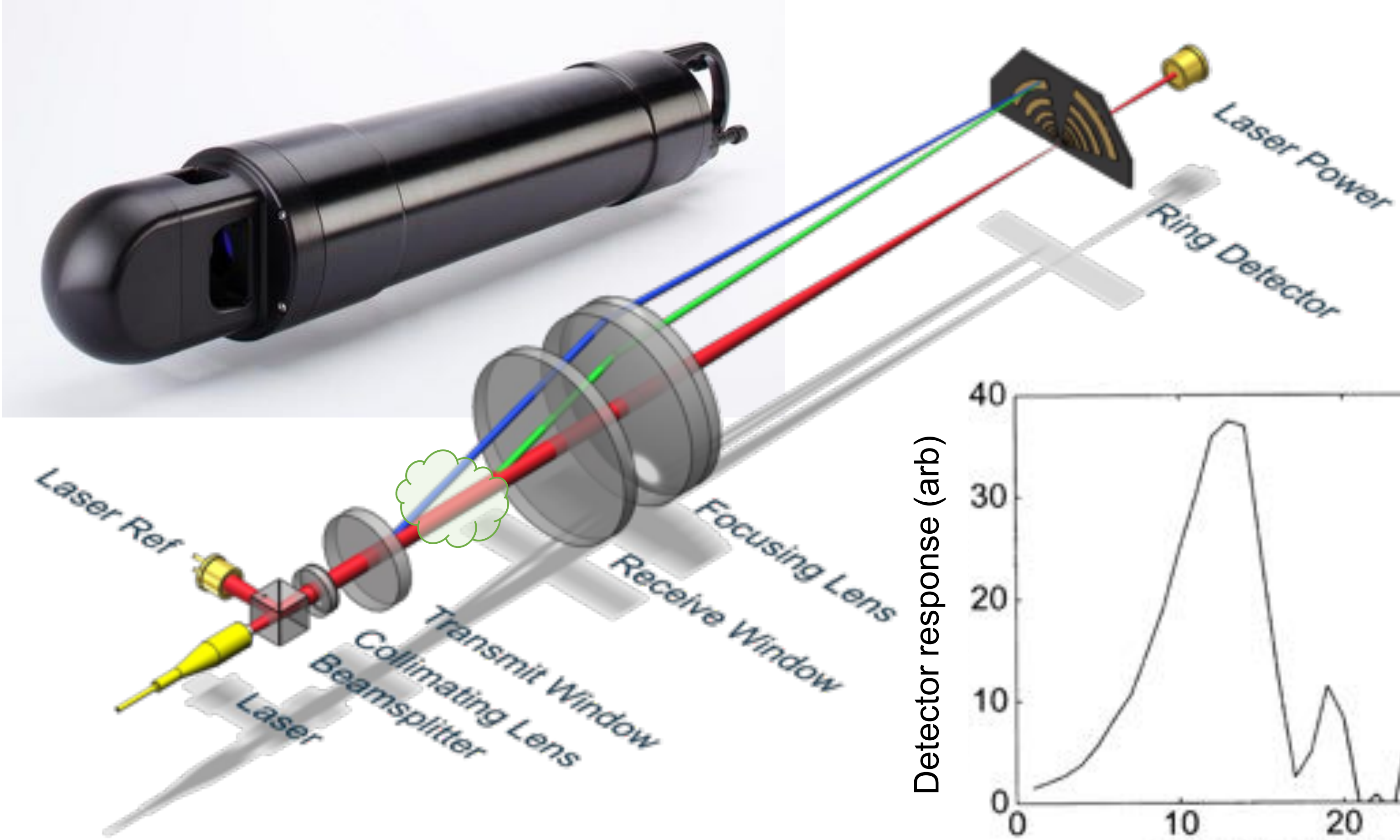
Ibsen photonics

Recall that near-forward scattering shape depends on particle size – "forward" problem

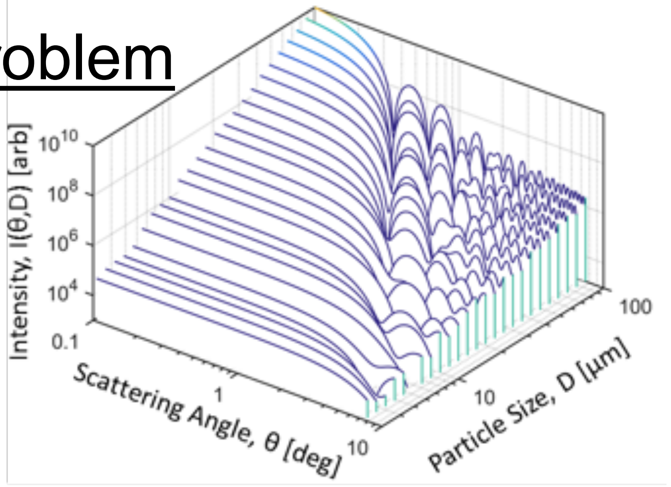
Calculations based on Mie theory for spheres
(other models could be used)



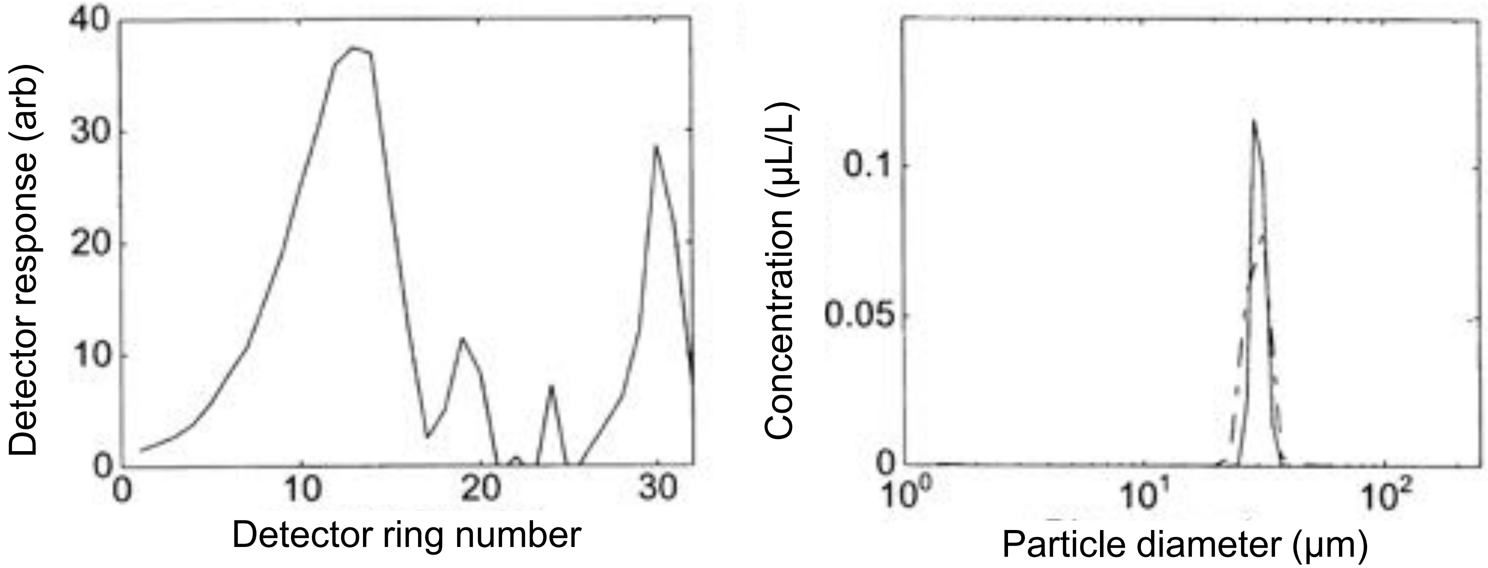
Example: near-forward scattering for particle sizing



Direct problem

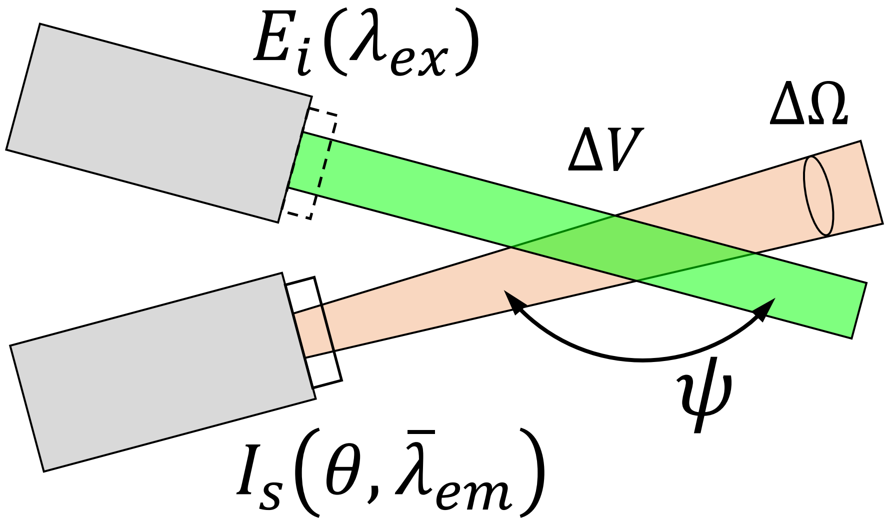


Inverse problem



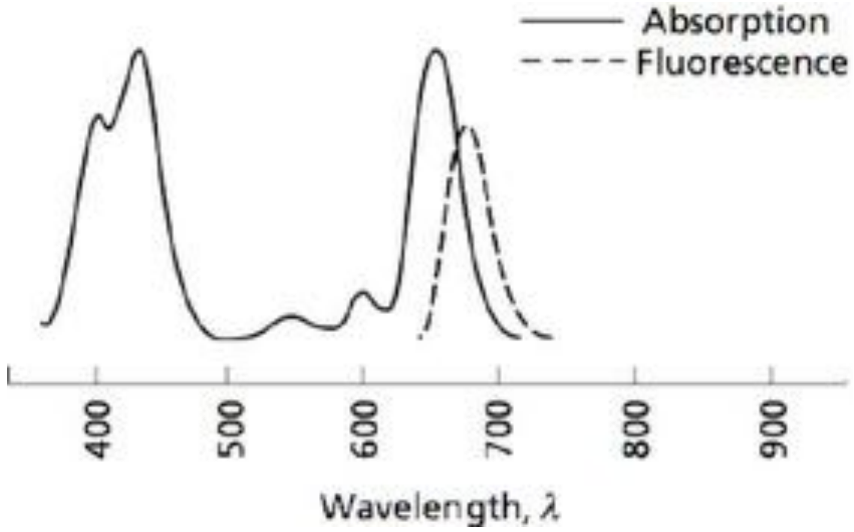
Near-forward light scattering depends on size of particles in sample. Measuring scattering at multiple angles allows you to estimate particle size distribution.

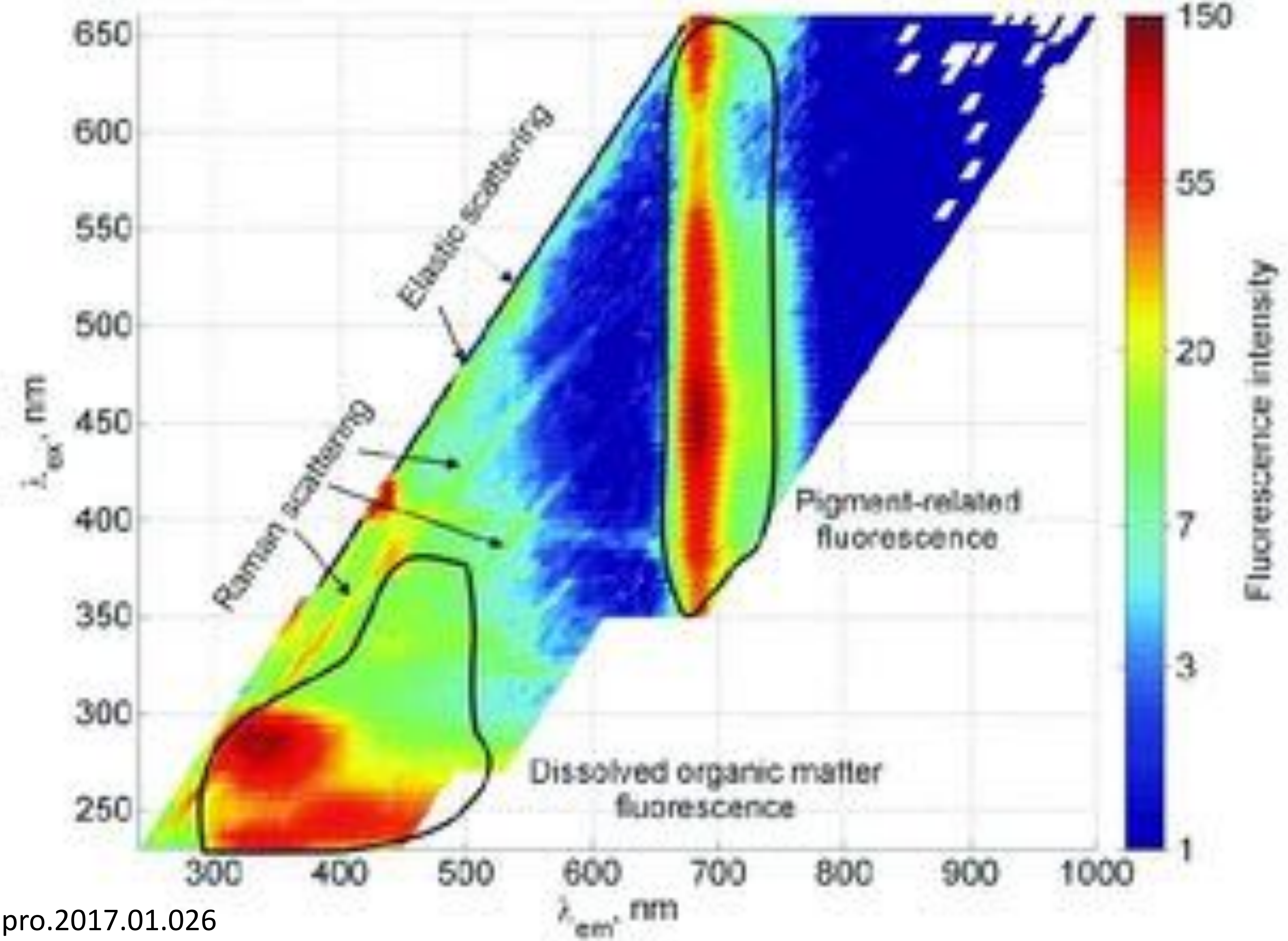
Measuring fluorescence is similar to measuring scattering



Use bandpass elements in the transmit and receive optics to define the “excitation” and “emission” bands around $\bar{\lambda}_{ex}$and$\bar{\lambda}_{em}$.

Example: chlorophyll





doi: 10.1016/j.phpro.2017.01.026

Fluorescence Exitation/Emission

P/N	Application	MDL	Linear Range	LED (CWL)	Excitation	Emission	Solid Standard
2300-251	CDOM/FDOM	0.1 ppb* 0.5 ppb**	0-1,500 ppb* 0-3,000 ppb**	365 nm	325/120 nm	470/60 nm	2300-902
2300-200	Chl *in vivo* (Blue Excitation)	0.03 µg/L	0-500 µg/L	460 nm	465/170 nm	696/44 nm	2300-901
2300-203	Chl *in vivo* (Red Excitation)	0.3 µg/L	>500 µg/L	635 nm	≤ 635 nm	> 695 nm	2300-901
2300-220	Fluorescein Dye	0.01 ppb	0-500 ppb	460 nm	400/150 nm	545/28 nm	2300-901
2300-253	Oil - Crude	0.2 ppb**	0-1,500 ppb**	365 nm	325/120 nm	410-600 nm	2300-902
2300-255	Oil - Fine (Refined Fuels)	0.4 ppm***	0-20 ppm***	255 nm	≤ 290 nm	350/50 nm	2300-902
2300-252	Optical Brighteners for Wastewater Monitoring	0.6 ppb **	0-2,500 ppb **	365 nm	325/120 nm	445/15 nm	2300-902
2300-231	Phycocyanin (Freshwater Cyanobacteria)	2 ppb[PC]	0-4,500 ppb[PC]	590 nm	590/30 nm	≥ 645 nm	2300-901
2300-230	Phycoerythrin (Marine Cyanobacteria)	0.1 ppb[PE]	0-750 ppb[PE]	525 nm	515-547 nm	≥ 590 nm	2300-901
2300-250	PTSA	0.1 ppb**	0-650 ppb**	365 nm	325/120 nm	405/10 nm	2300-902
2300-210	Rhodamine Dye	0.01 ppb	0-1000 ppb	530 nm	535/60 nm	590-715 nm	2300-901
2300-256	Tryptophan for Wastewater Monitoring	3 ppb	5,000 ppb	275 nm	-	350/55 nm	2300-902
2300-240	Turbidity	0.05 NTU	0-1,500 NTU	850 nm	850 nm	850 nm	N/A

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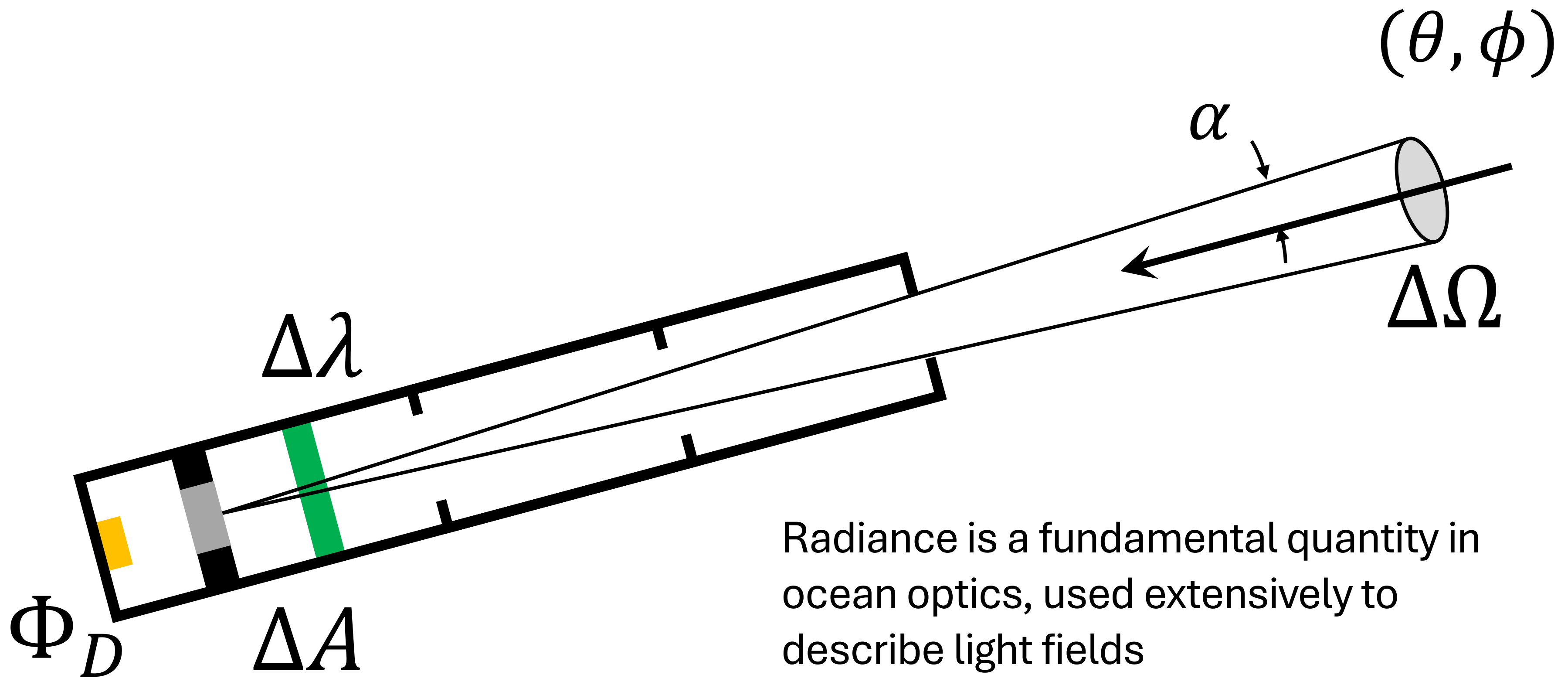
http://docs.turnerdesigns.com/t2/doc/spec-guides/998-2381.pdf

Measuring radiance – Gershun tube

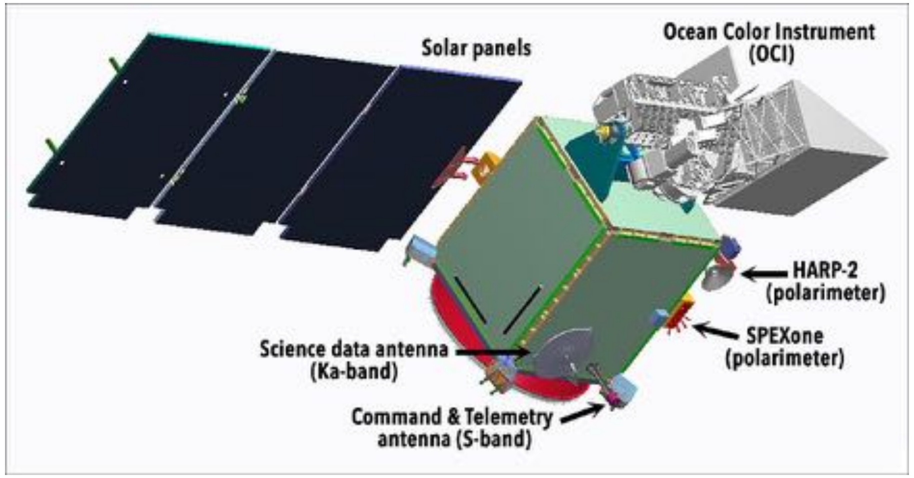


Radiance is a fundamental quantity in ocean optics, used extensively to describe light fields

$$L(\theta, \phi, \lambda) = \frac{\Phi_D}{\Delta A\ \Delta\Omega\ \Delta\lambda} \quad \left(\frac{\mathrm{W}}{\mathrm{m^2\ sr\ nm}}\right)$$

http://www.oceanopticsbook.info/view/light_and_radiometry/geometrical_radiometry

PACE Plankton, Aerosol, Cloud, ocean Ecosystem

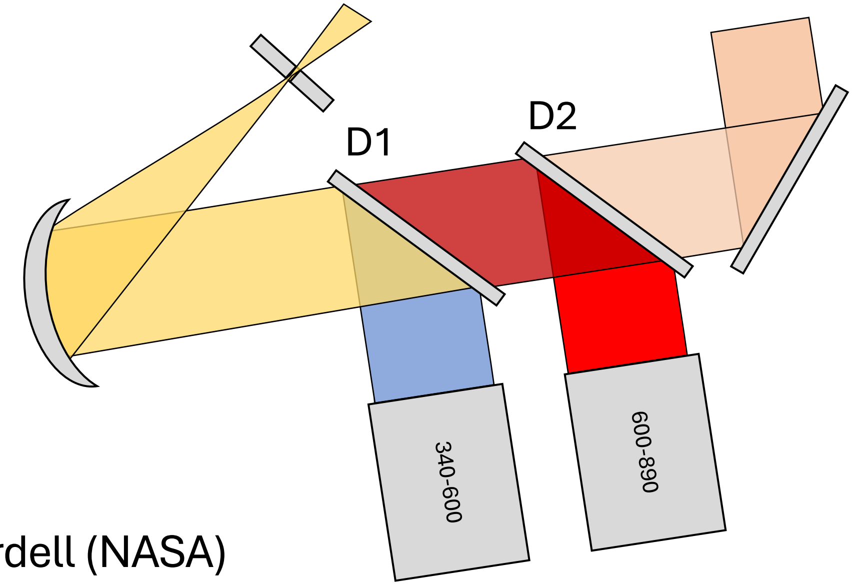


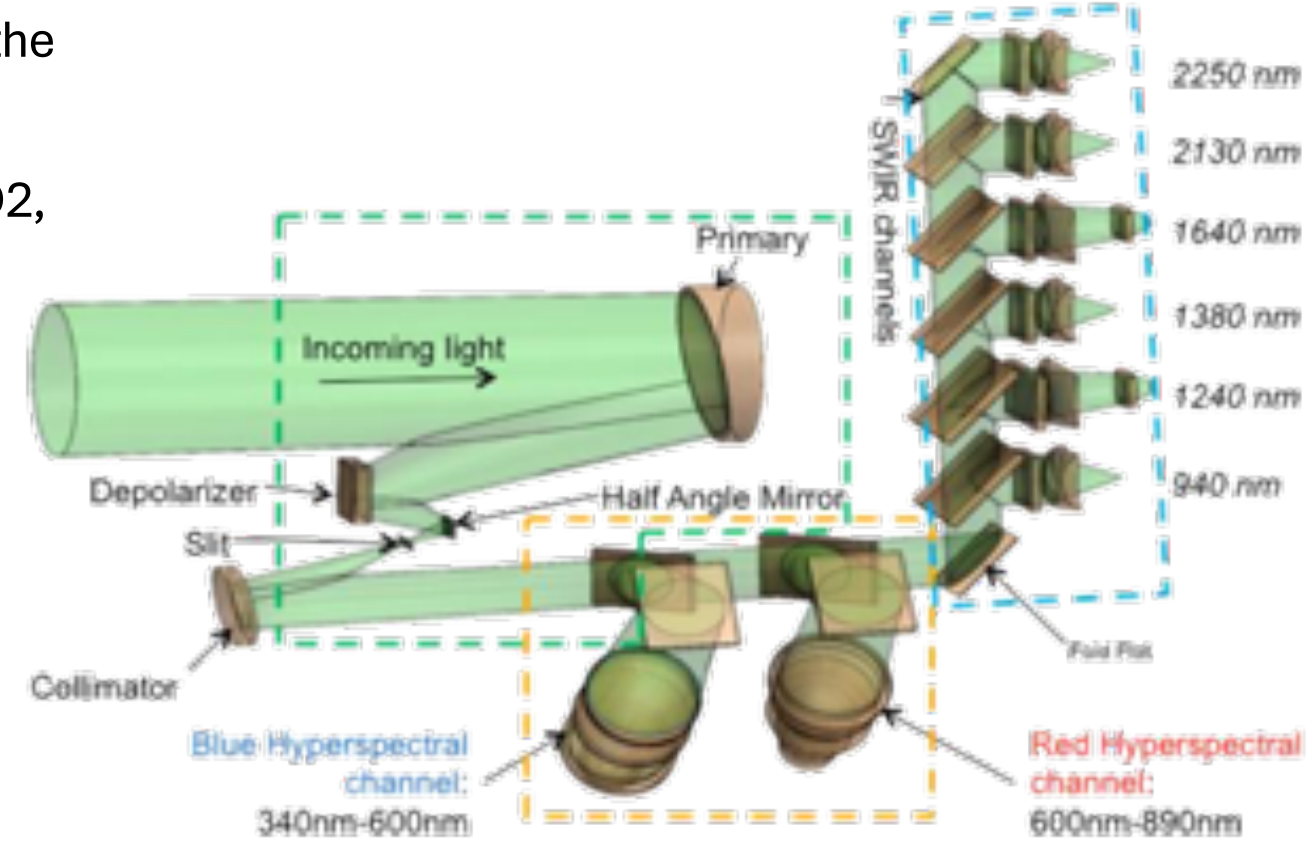
Ocean color remote sensors are radiometers

PACE/OCI measures 340 – 890 nm at 5 nm resolution + SWIR

Mirrors are used to fold, transmit, and collimated the incoming light

Separation into two systems using dichroics D1, D2, each has a grating spectrometer





J Werdell (NASA)

Parting thoughts…

Both simple and complex optical instruments use similar optics and design approaches

Common themes include characterization, calibration, data processing, validation – always good to cross-compare different approaches

Understanding a bit about how optical instruments work will help to understand data and potential issues with methods

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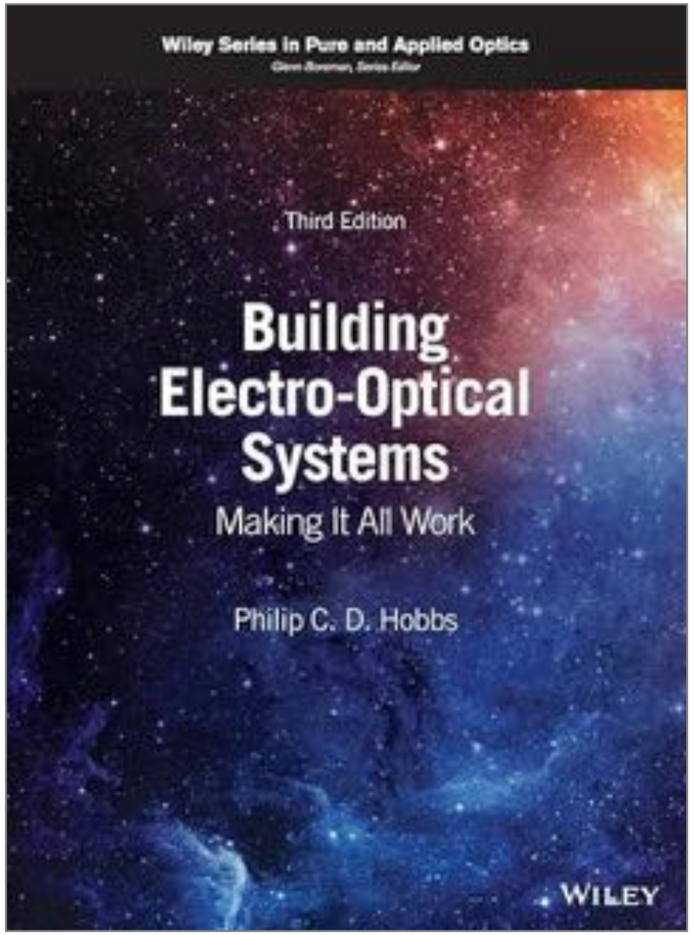
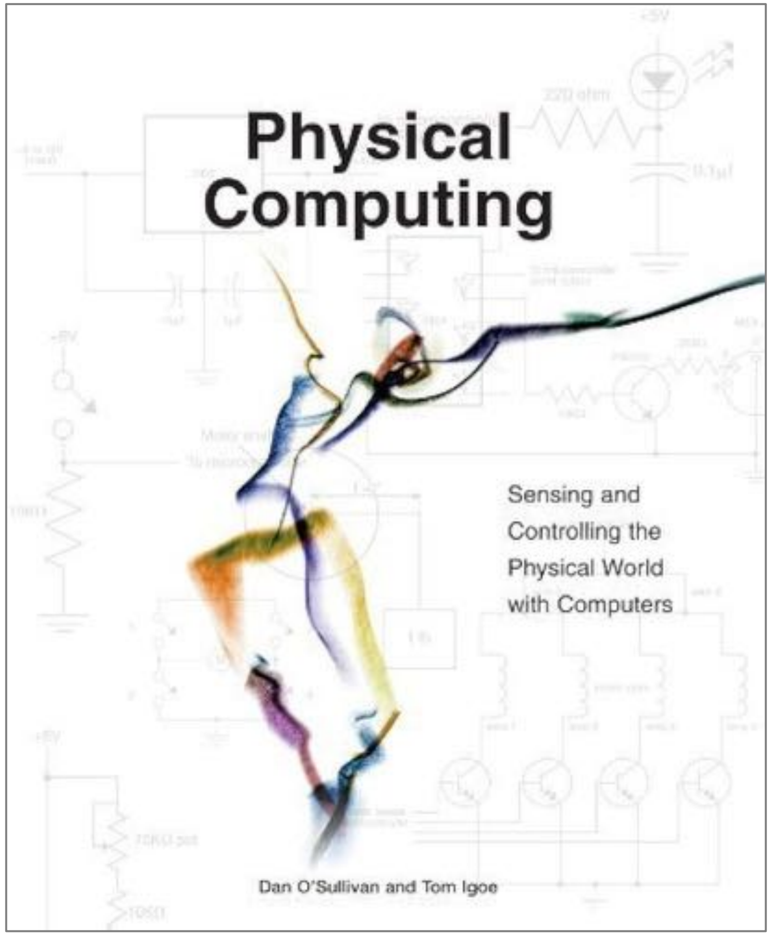
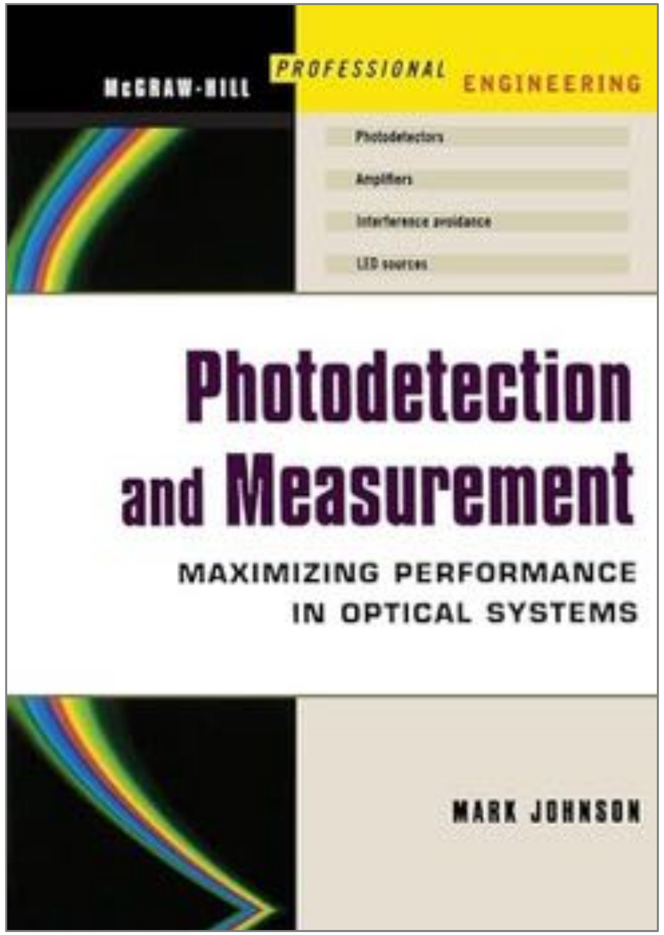


P.C.D. Hobbs, "Building Electro-Optical Systems" (3rd Ed, 2022)



D.O Sullivan and T. Igoe, "Physical Computing: Sensing and Controlling the Physical World with Computers" (2004)



M. Johnson, "Photodetection and Measurement" (2003)

Unofficial homework…

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Article

In situ Measurements of Phytoplankton Fluorescence Using Low Cost Electronics

Thomas Leeuw *, Emmanuel S. Boss and Dana L. Wright

Article | Open Access | Published: 20 June 2022

scientific reports

Open-source, low-cost, in-situ turbidity sensor for river network monitoring

Jessica Droujko & Peter Molnar

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sensors
ISSN 1424-8220
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Article

An Affordable Open-Source Turbidimeter

Christopher D. Kelley [1,*], Alexander Krolick [2], Logan Brunner [1], Alison Burklund [1], Daniel Kahn [1], William P. Ball [1] and Monroe Weber-Shirk [3]