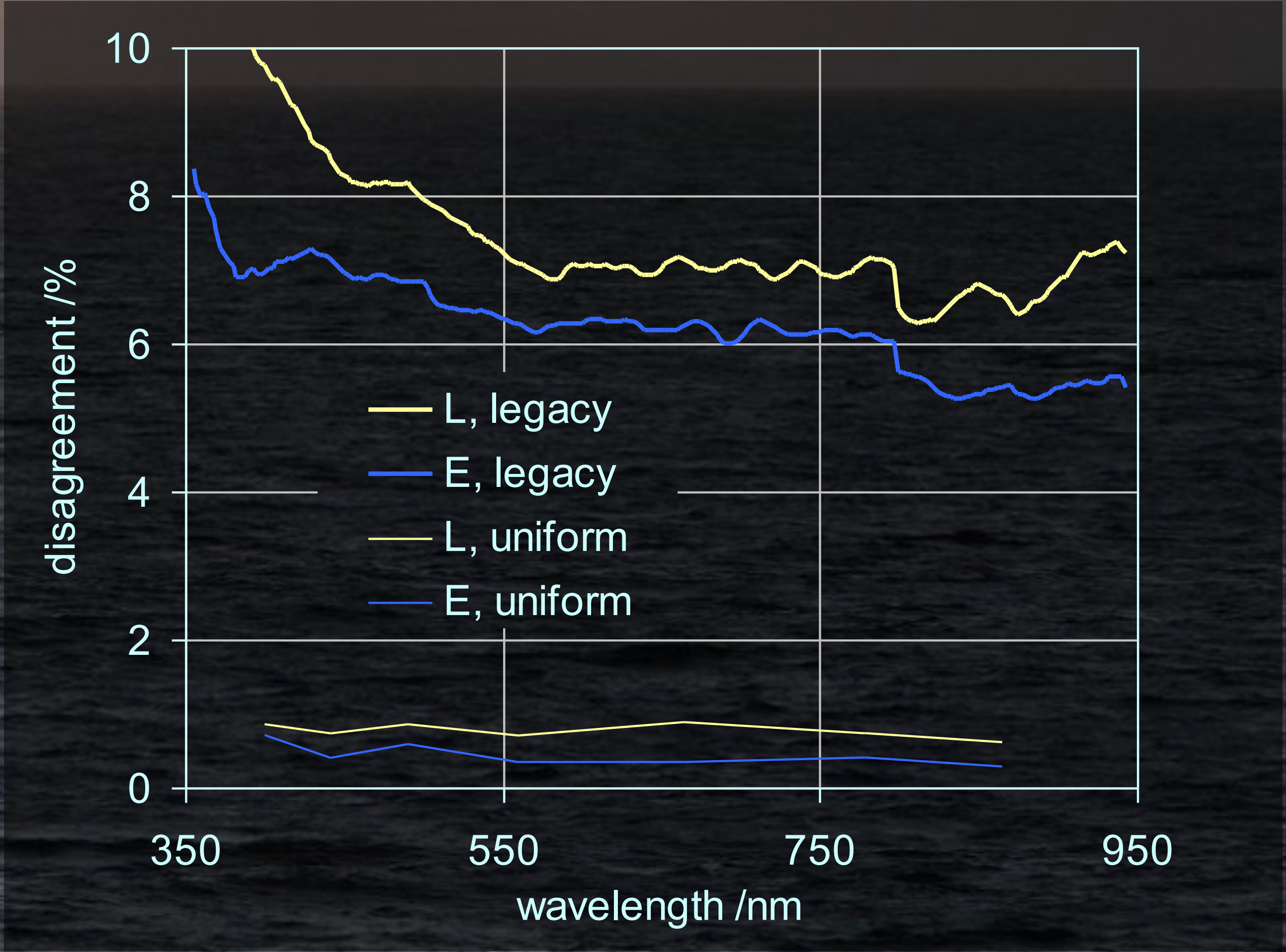
Radiometric calibration guidelines

Ilmar Ansko
Tartu Observatory, ESTONIA

Tõravere 2025

On the importance of calibration

During the FRM4SOC LCE2 experiment, participating radiometers were used to measure stable laboratory sources.
Measurement geometry was close to the calibration geometry.
Results were evaluated by using "legacy" (provided by the users) and the fresh "uniform" responsivity coefficients.
"Disagreement" was calculated as standard deviation of the results of over 40 participating radiometers.



Who will calibrate?

The OC community needs a network of laboratories able and willing to perform the cal/char measurements and to disseminate the results in expected format.

One lab is not enough: workload too high and impossible to properly validate the results. Cooperation between the labs is critically important.

Setting up the cal/char facilities

•To be solved first: the long-term sustainability, i.e. the financing and human resources.
•If starting from scratch, visit other labs. Copy as much as possible.
•Decide how to establish the traceability: not only the radiometric standards, but also the electrical, mechanical nad environmental equipment needs SI-traceable calibration.
•Find the space and collect the necessary equipment. Most of the equipment is low-tech and can be built in-house.
•Develop and document the measurement methods. Validate before commissioning.

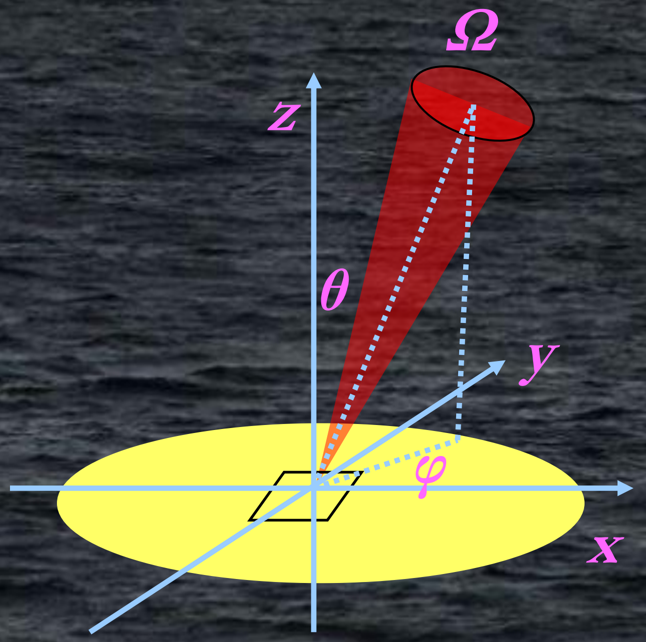
Running the cal/char facilities

- Keep track of everything relevant: access to the equipment, serial numbers, cal history, failures, environmental conditions, software versions etc.
- Keep the documentation tidy and backed up safely.
- Create the calibration plan of your equipment and follow it.
- Cross-validate your standards (by using 2-3 calibrated FEL lamps, by recording lamp voltages, monitor signals etc.)
- Find the ways to intercompare with fellow labs.
- Try to involve more people.
- Create software to automatize the boring parts.
- Keep going all this at least next 30 years.

Radiometric quantities

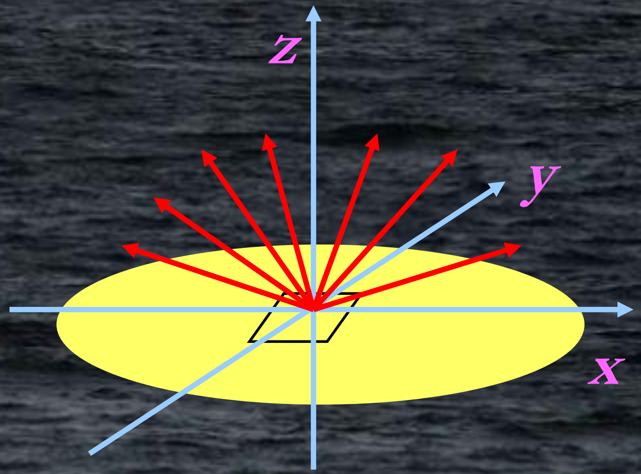
The basic quantity in radiometry is optical power *P*, measured in watts: 1 W= 1 J/s.

Radiance $L(\varphi,\theta,\lambda)$: power, emitted from the unit area of the source into unit solid angle.
Unit: $\mathrm{W \cdot m^{-2} sr^{-1}}$ or $\mathrm{W \cdot m^{-2} sr^{-1} nm^{-1}}$



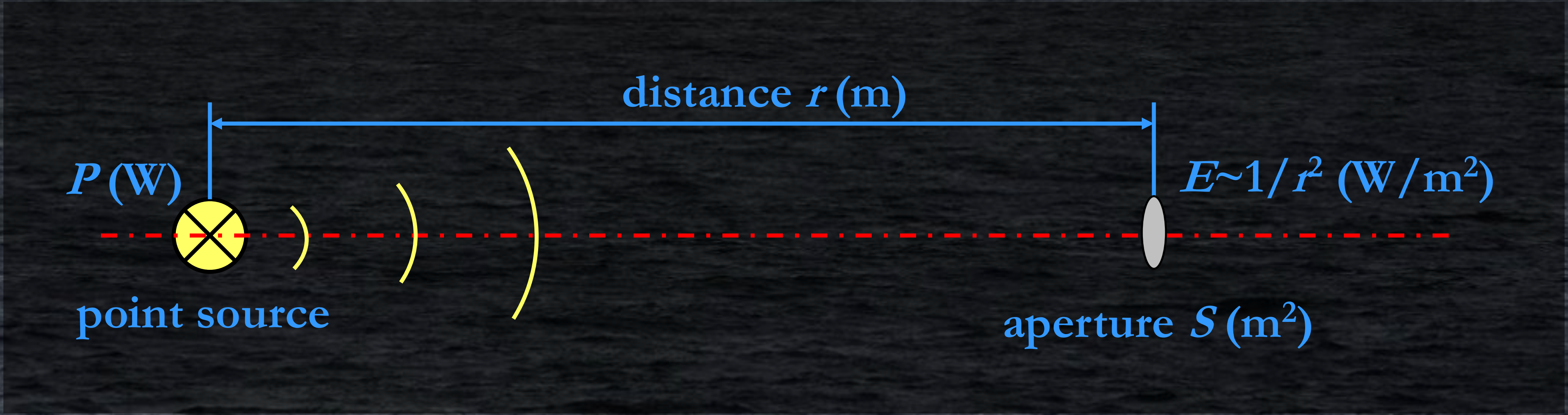
Irradiance $E(\lambda)$: power, emitted from the unit area.
Unit: $\mathrm{W \cdot m^{-2}}$ or $\mathrm{W \cdot m^{-2} nm^{-1}}$

$$E(\lambda)=\iint L(\varphi,\theta,\lambda)\,\mathrm{d}\varphi\,\mathrm{d}\theta$$



For hemisphere: $\Omega=\iint \mathrm{d}\varphi\,\mathrm{d}\theta=2\pi\ sr$

Irradiance field of the point source

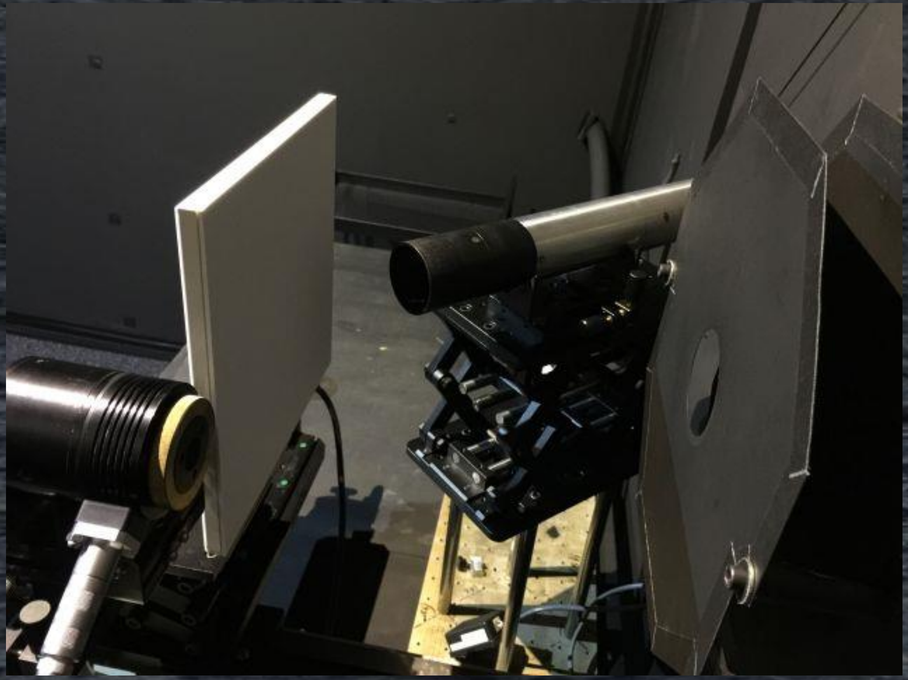


Lambertian surface

Radiance $L(\varphi,\theta,\lambda)$ does not depend on the polar angles φ,θ (the surface is perfectly diffuse):

$$E(\lambda)=\iint L(\varphi,\theta,\lambda)\,\mathrm{d}\varphi\,\mathrm{d}\theta=\pi L(\lambda)$$

Lambertian targets are widely used for calibration and characterization purposes.



diffuse reflectance target

integrating sphere

Hyperspectral radiometers for OC

Sea-Bird HyperOCR

TriOS RAMSES

Water Insight WISP3

SR-3500

In-situ Marine Optics DALEC

Software & output formats

Depend on the manufacturer's choice. Always prefer raw analog-to-digital output.
Some data need to be logged manually (e.g. lamp and panel serial numbers).

RAMSES:
Data acquisition and file conversion: "MSDA_XE", records binary (MS ACCESS) or ASCII datafiles.

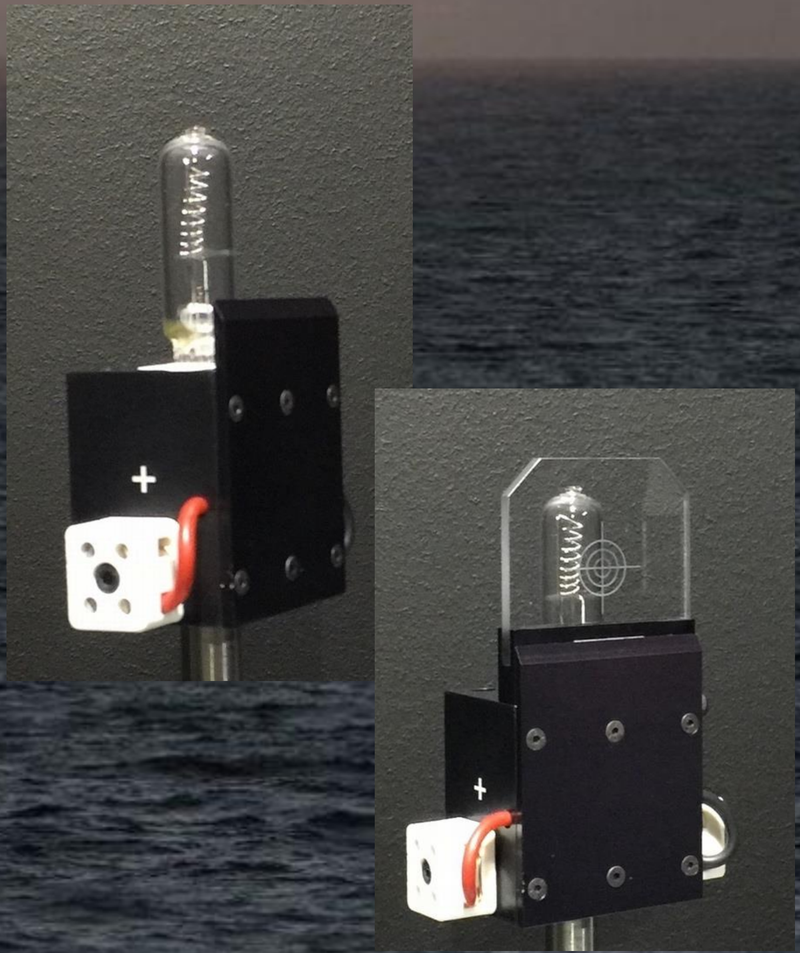
HyperOCR:
Data acquisition: "SatView", records binary datafiles.
Binary-to-ASCII datafile conversion: "SatCon".

Radiometric responsivity units

RAMSES:	
irradiance responsivity=output signal/irradiance	[1/(mW·m^{-2}nm^{-1})]
radiance responsivity=output signal/radiance	[1/(mW·m^{-2}nm^{-1}sr^{-1})]
HyperOCR:	
irradiance responsivity=irradiance/output signal	[μW·cm^{-2}nm^{-1}]
radiance responsivity=irradiance/output signal	[μW·cm^{-2}nm^{-1}sr^{-1}]
DALEC:	
irradiance responsivity=irradiance/output signal	[W·ms^{-1}m^{-2}nm^{-1}]
radiance responsivity=irradiance/output signal	[W·ms^{-1}m^{-2}nm^{-1}sr^{-1}]

Types of FEL lamps and alignment jigs

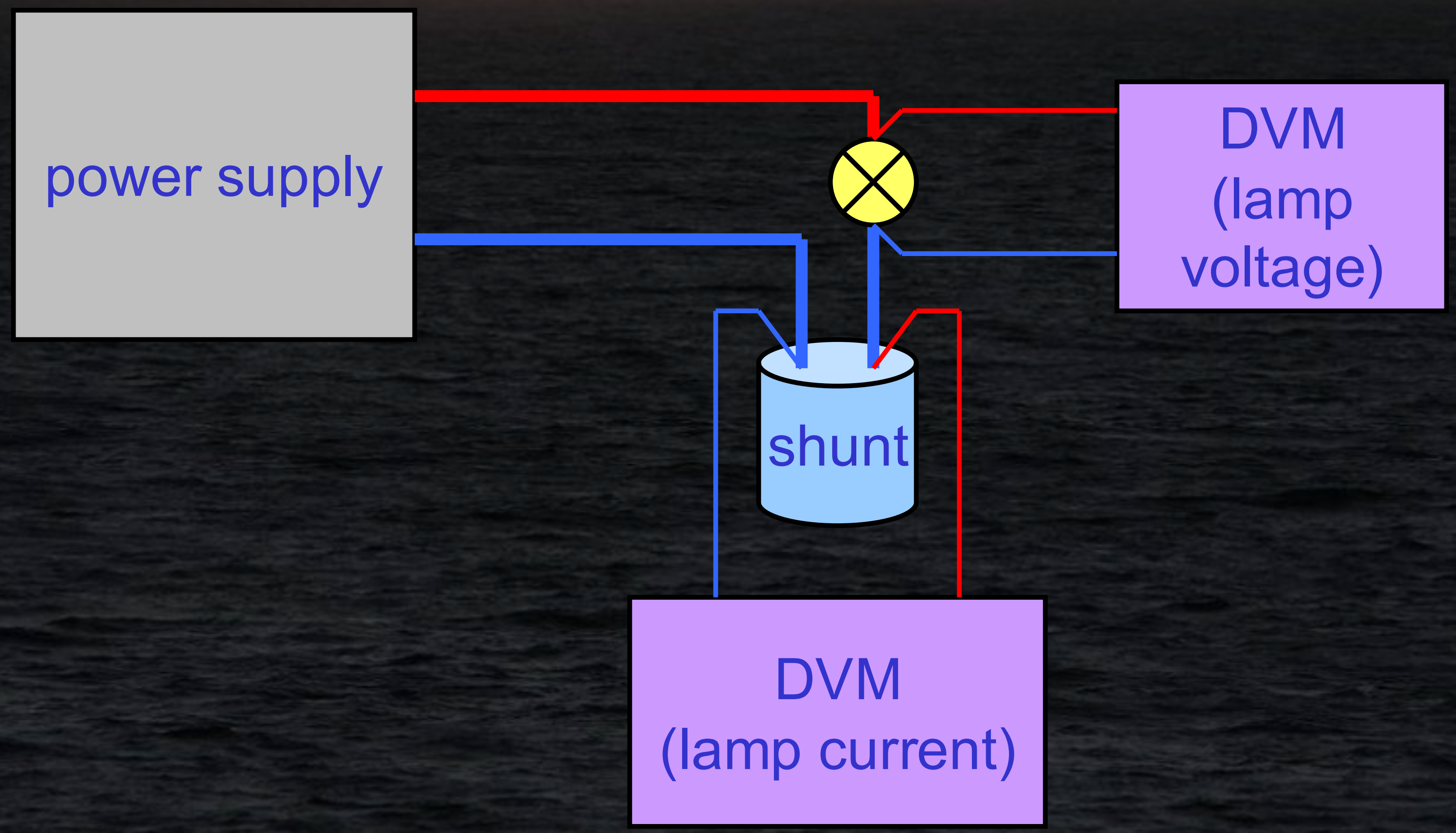
NIST



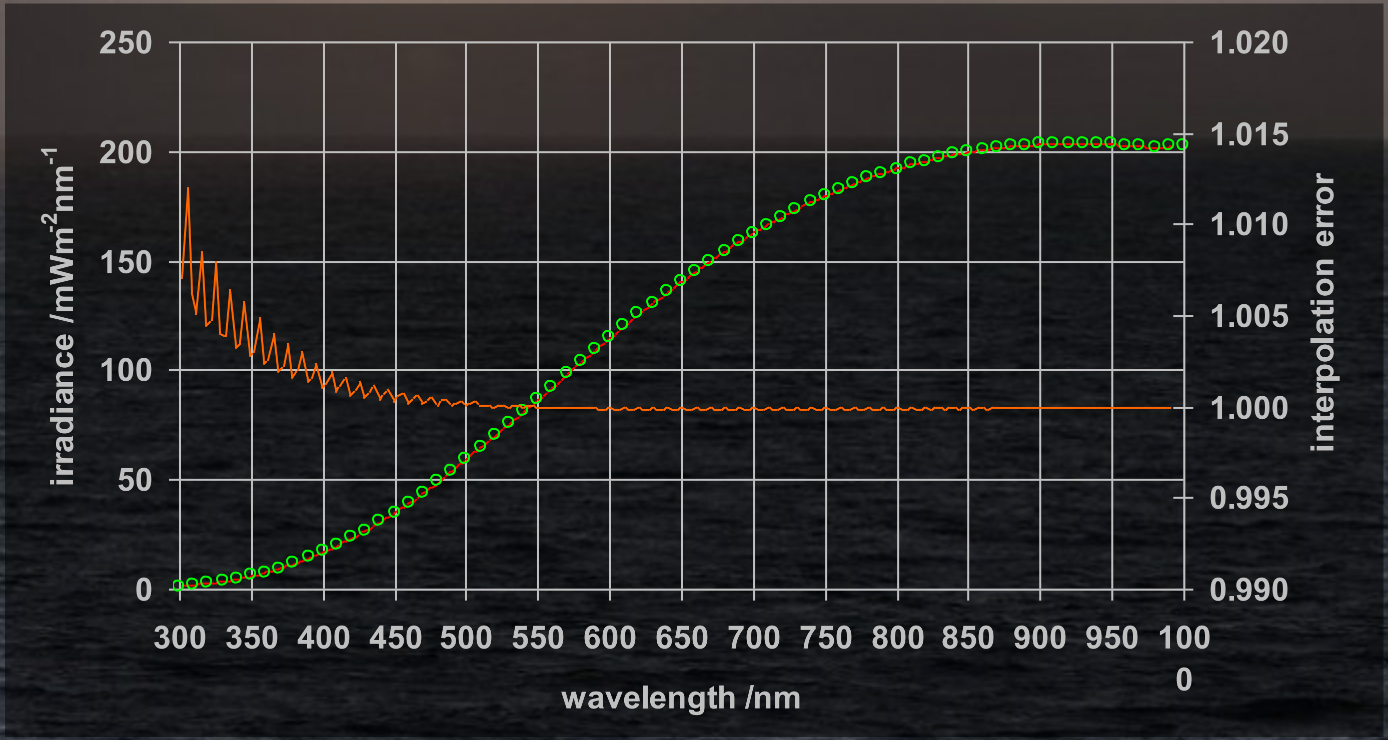
Gigahertz

Oriel

Connecting the FEL lamp



Interpolation



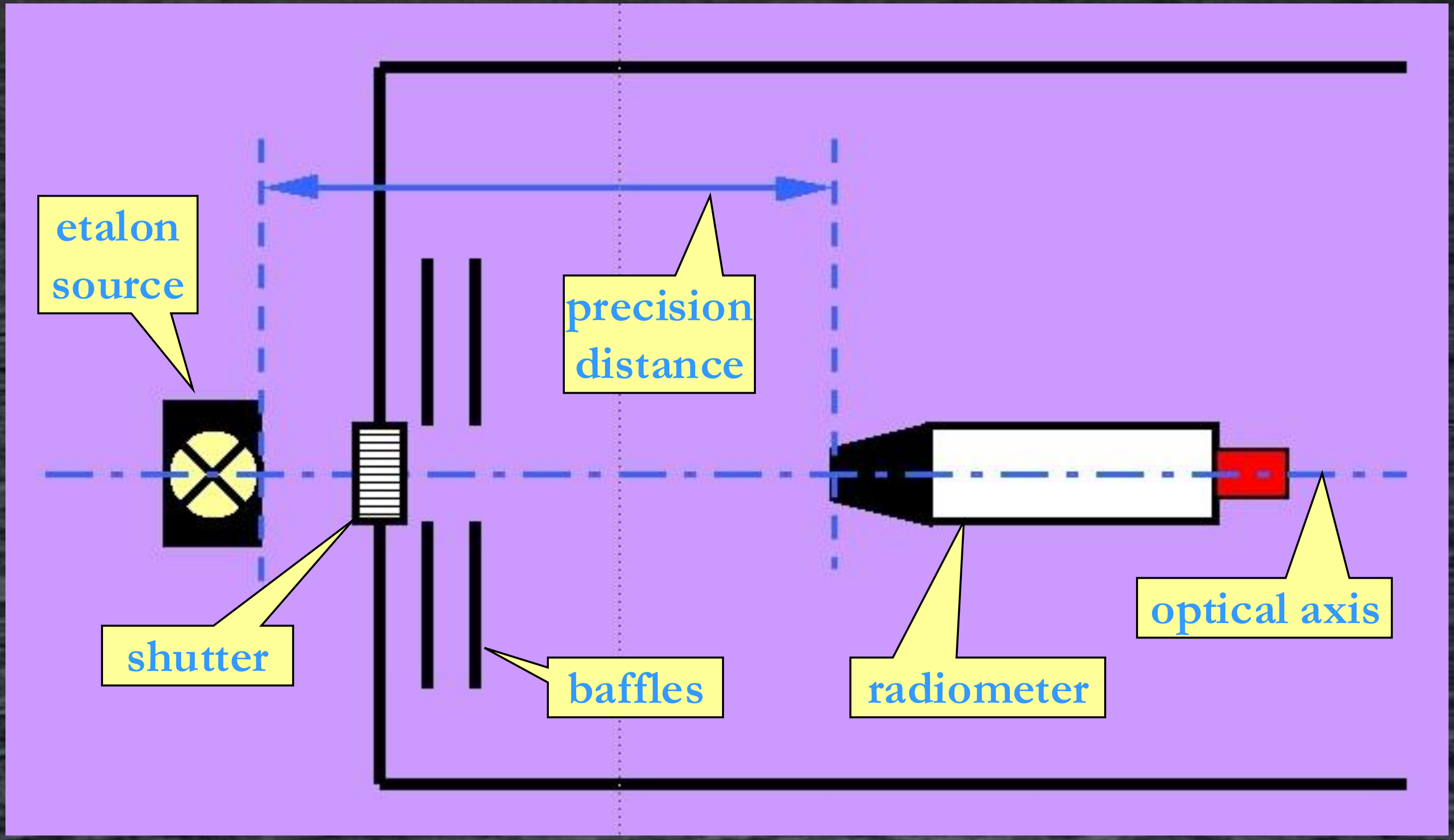
Each hyperspectral module has individual pixel-to-wavelength relationship.

The lamp (and panel) data is given with arbitrary wavelength step, e.g. 10 nm.

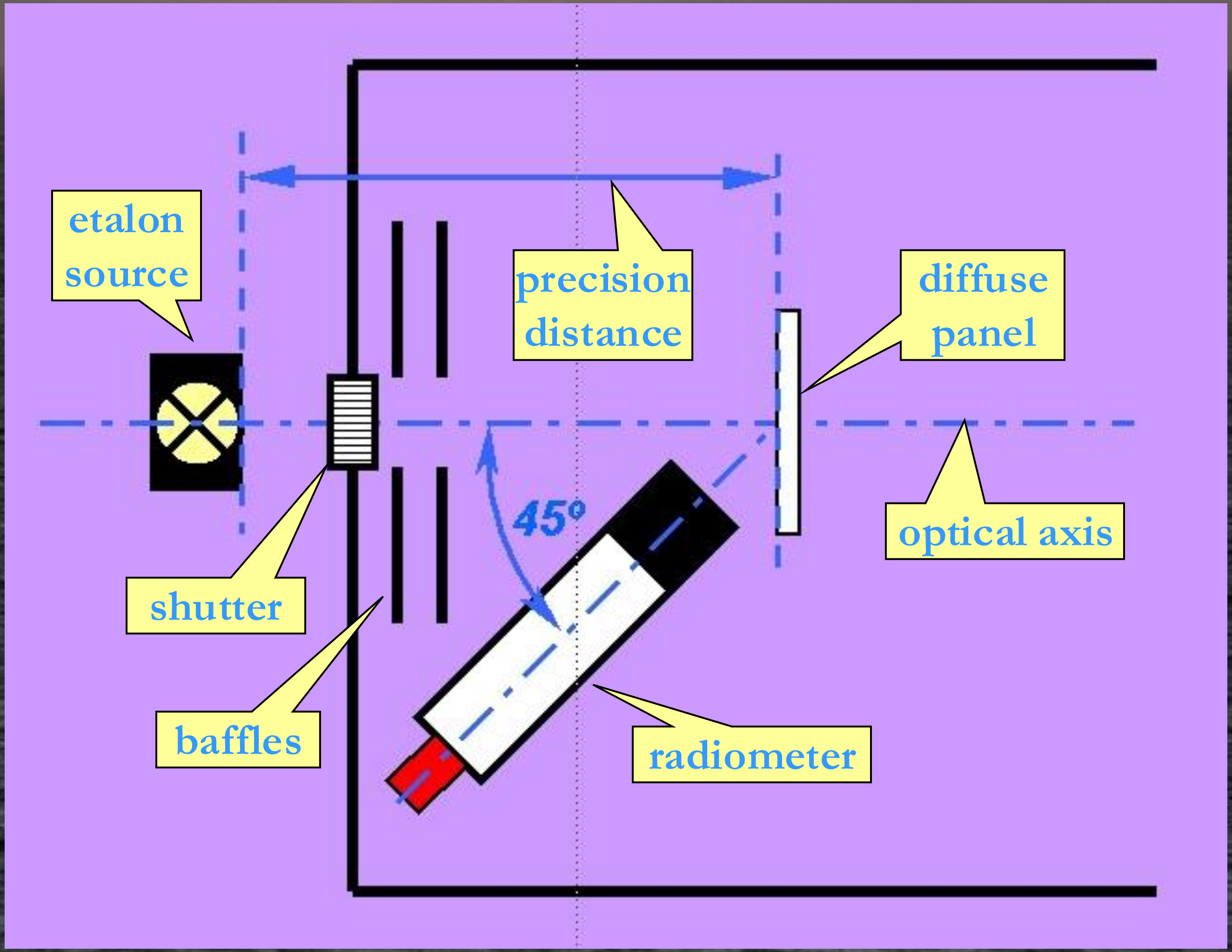
Different interpolation methods are available, from "blind" polynomials to model-based.

Will be described elsewhere.

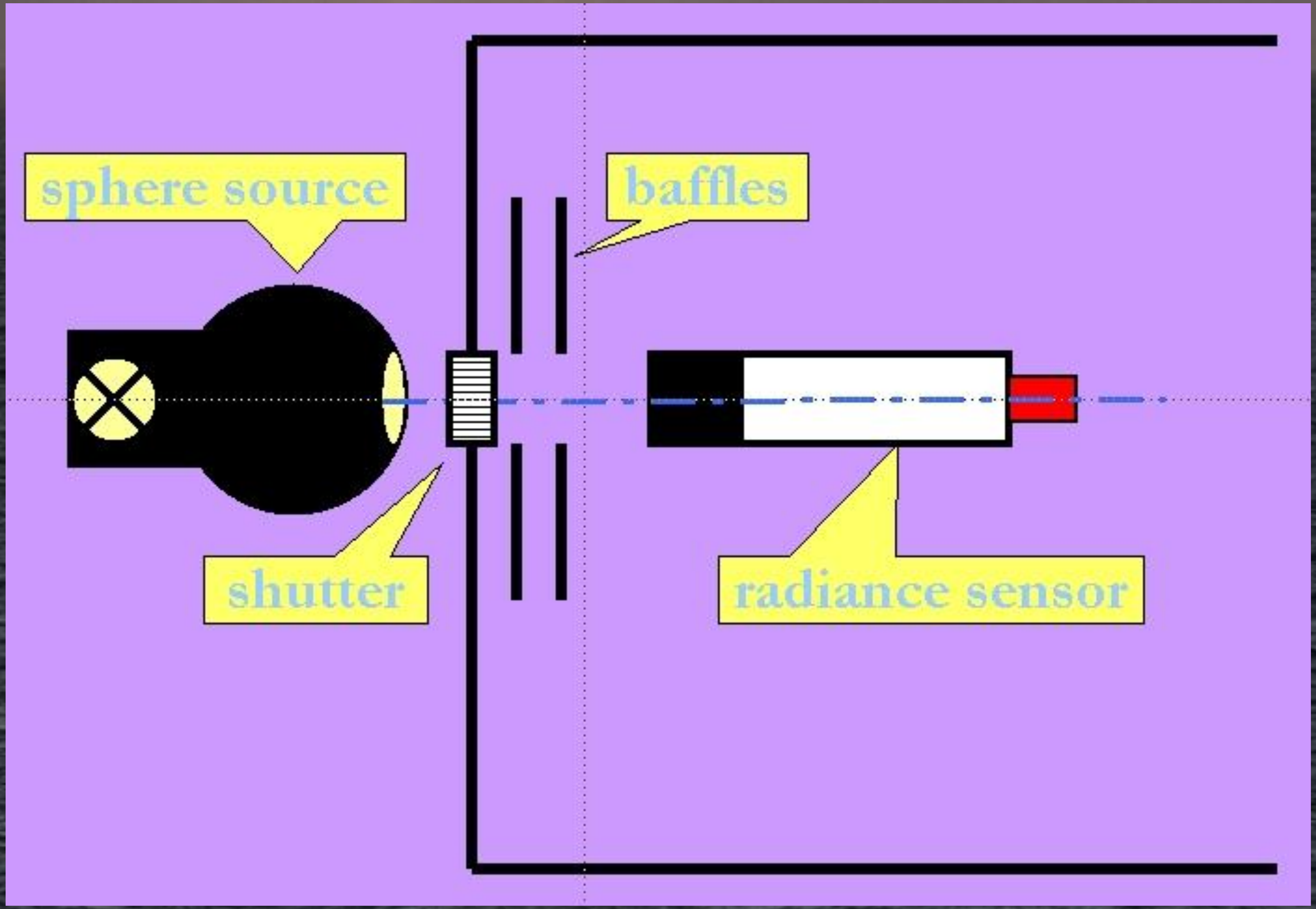
Radiometric calibration setup for irradiance



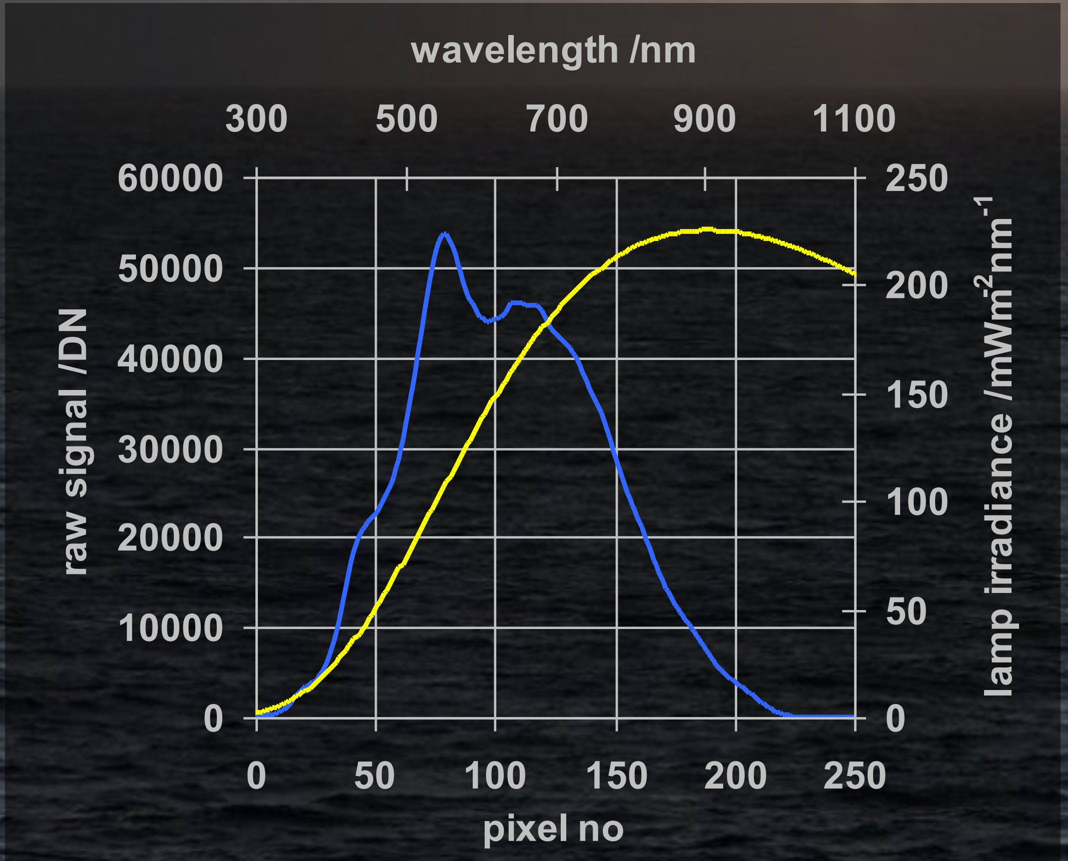
Radiometric calibration setup for radiance #1



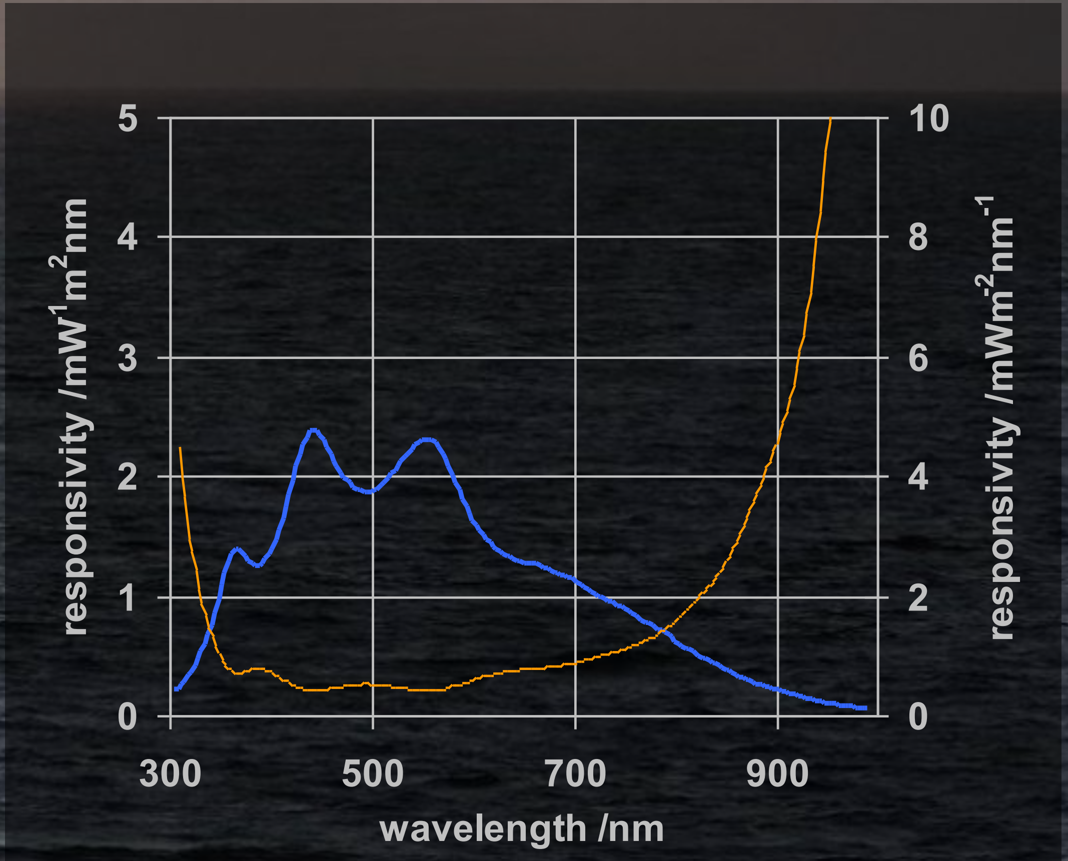
Radiometric calibration setup for radiance #2



Example spectra



Typical raw spectrum when measuring Planckian source with a SI-based array spectrometer.



Typical radiometric responsivity, two different units.

Why raw signals are needed

$$\text{CalibratedFieldSignal} = \frac{\text{RawFieldSignal*}}{\boxed{\text{CalFactor}}} = \frac{\text{RawFieldSignal*} \cdot \text{EtalonIrradiance}}{\text{RawCalSignal*}}$$

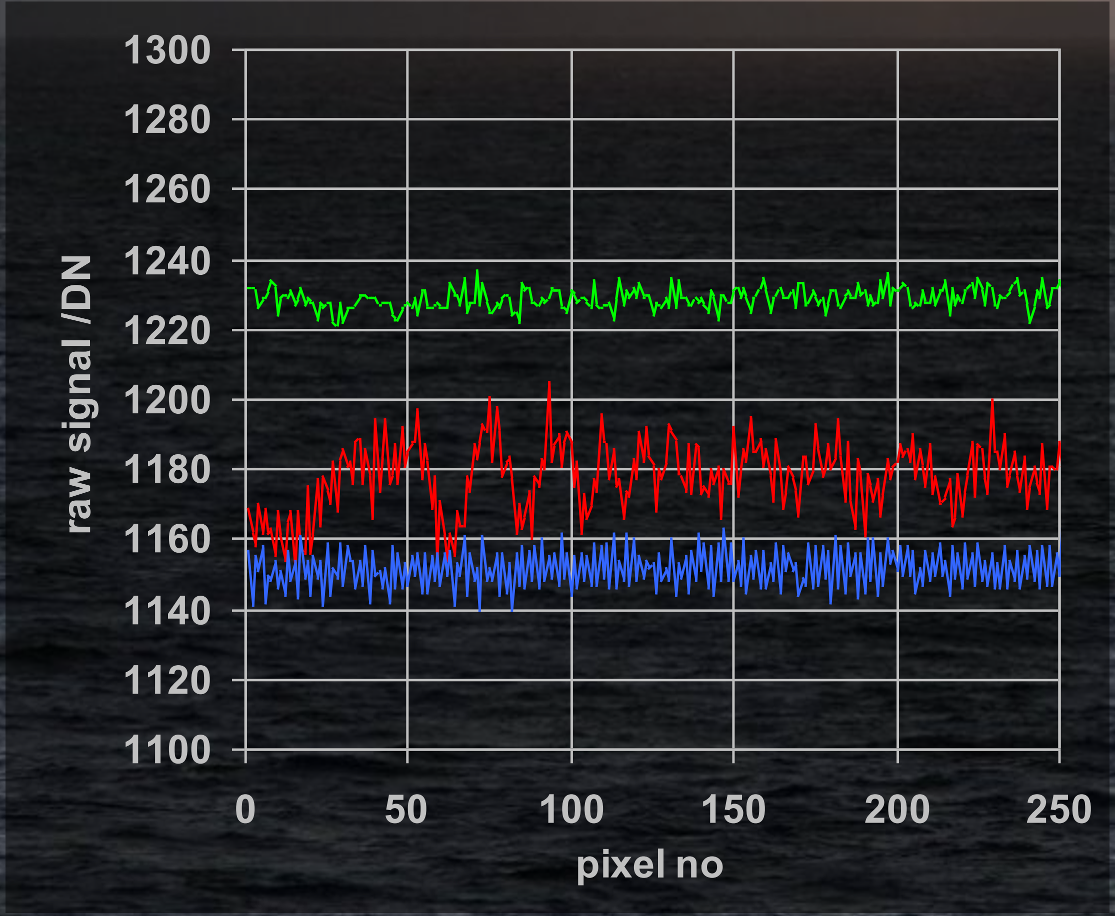
raw signals can be corrected for
non-linearity, spectral straylight etc.

*Dark is subtracted

Dark signal

Dark signal origins from the light sensor and from the front-end electronics.
Dark signal shall be subtracted from the target signal before any further processing.
Dark signal depends on the temperature and on the integration time.
Dark signal shall be measured as close as possible to the target signal
in order to avoid errors due to the thermal drift.
Dark signal shall be measured with the same integration time as the target signal
(be aware of automatic integration time settings!).
Using of the stored or modelled dark signals is strongly not recommended.

Dark signal: detection of misbehaviour



Dark signal can be sometimes used to detect hardware problems.
No special equipment needed.
Immunity to the electromagnetic interferences can be examined.

perfectly random dark signal

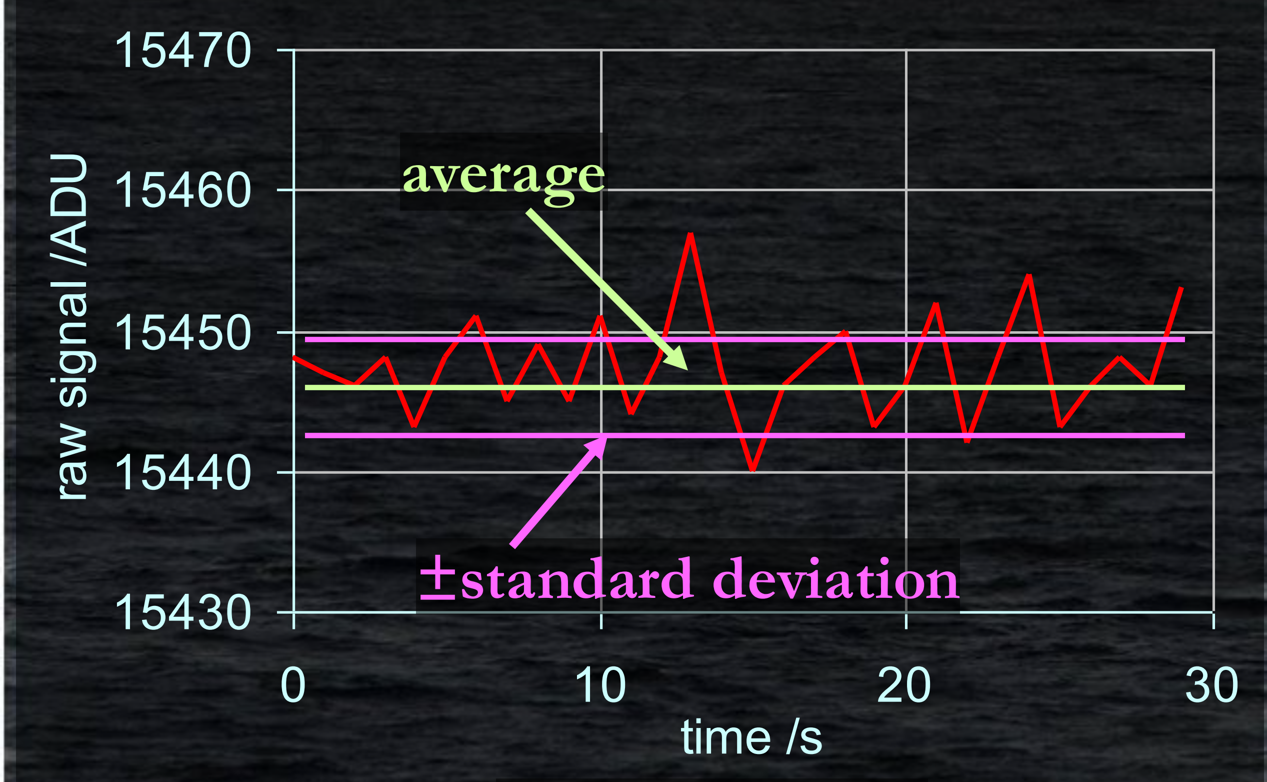
dominating periodic component means noisy electronics or noisy environment

Dark vs. background signal

Dark signal : the optical signal is completely blocked by the internal or external shutter.
Background signal: only the direct path between the source and the detector is blocked.
When setting up the calibration measurement, examine the differences between the dark and the background readings.
The background signal can be reduced with the help of baffling, painting etc.

Uncertainty of calibration: signal-to-noise ratio (*SNR*)

Noise is random change of the output signal when measuring constant input.
Origin: fundamental processes in the underlying opto-electronical components.
Noise magnitude depends on the signal level and temperature.



time domain

spectral domain

Uncertainty of calibration: signal-to-noise ratio (*SNR*)

raw signals

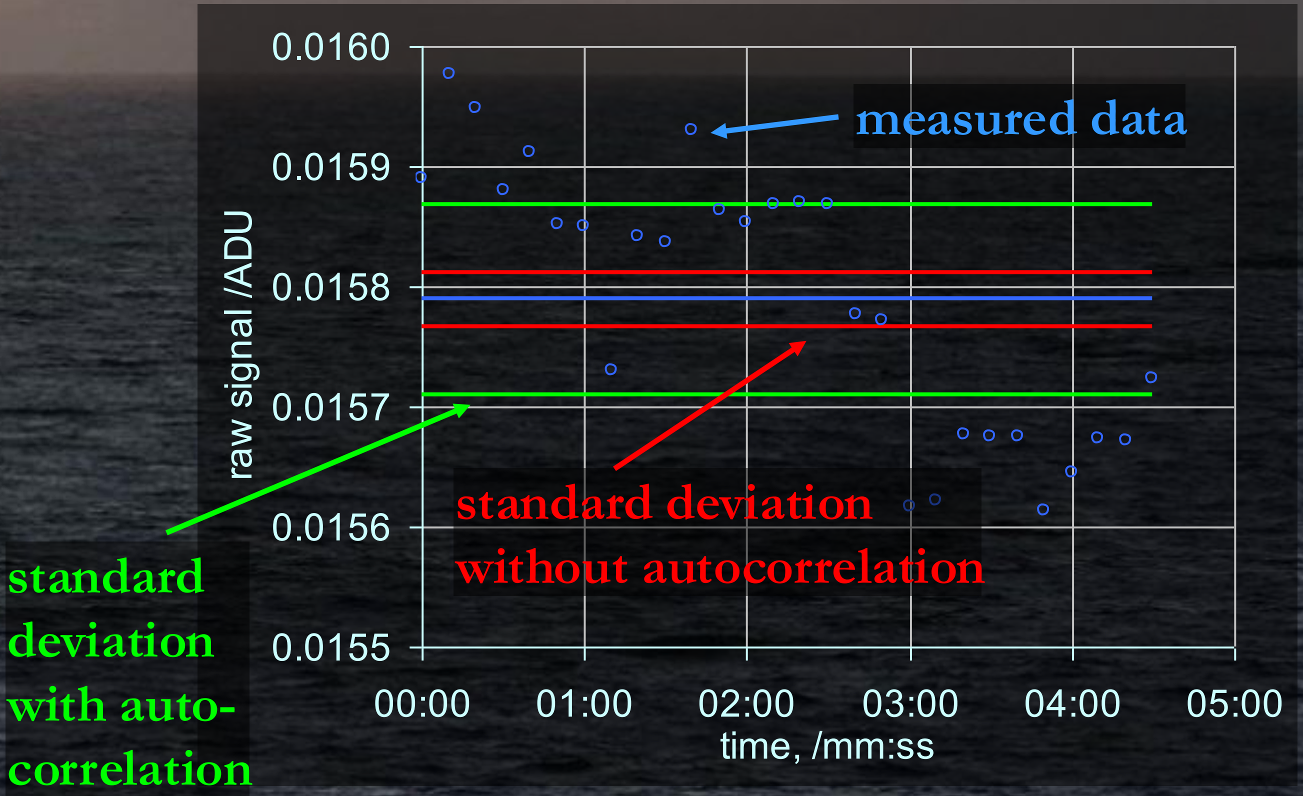
$$SNR = \frac{S_{light} - S_{dark}}{\sqrt{\sigma_{light}^2 + \sigma_{dark}^2}}$$

standard deviations

Be aware of temporal drifts when using standard deviation of the mean:

$$\sigma \rightarrow \frac{\sigma}{\sqrt{nf}}$$

nf: effective degrees of freedom, typically smaller than the number of averaged values.

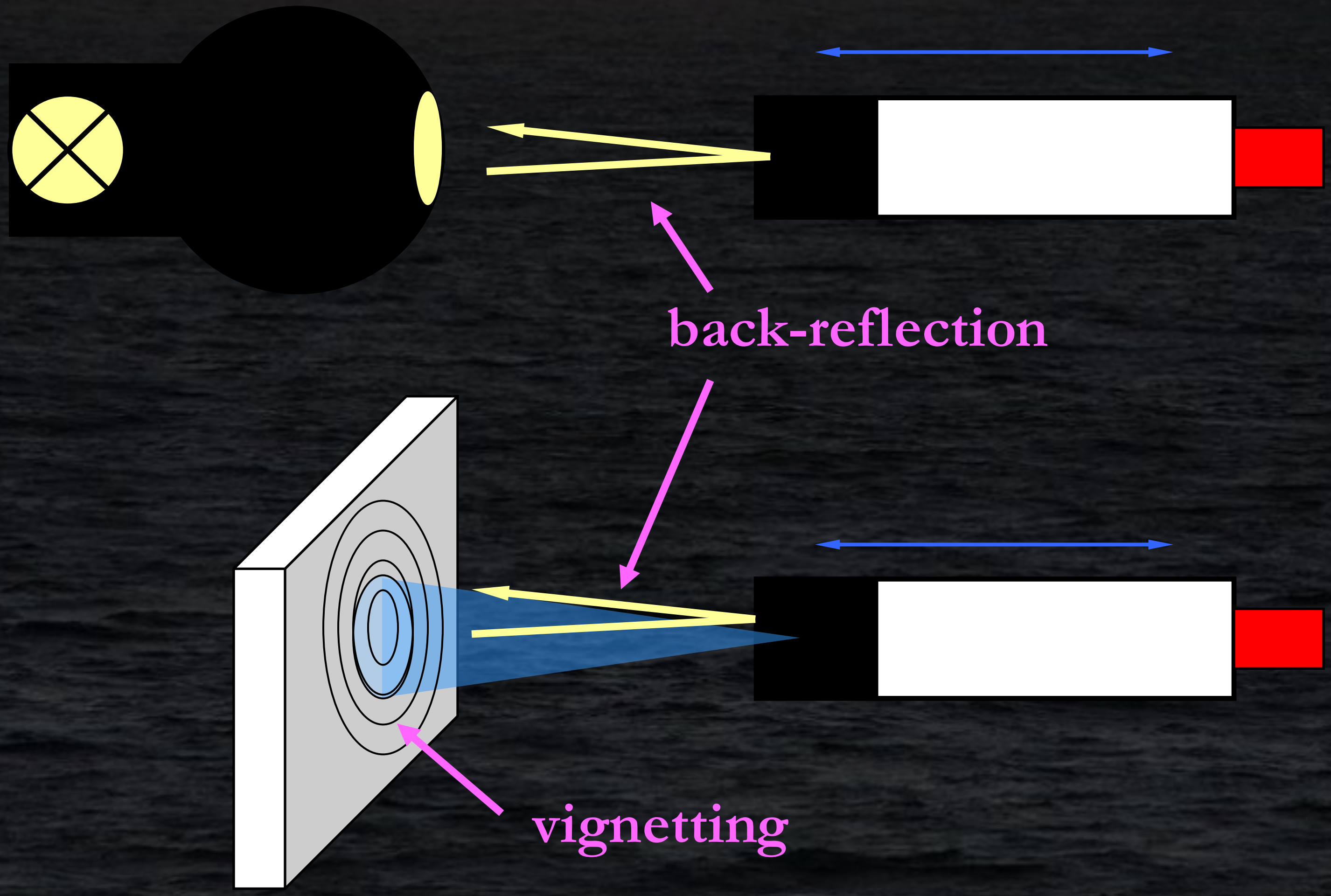


Drift of the time series shall not exceed 10% of the standard deviation. Otherwise, take autocorrelation into account.

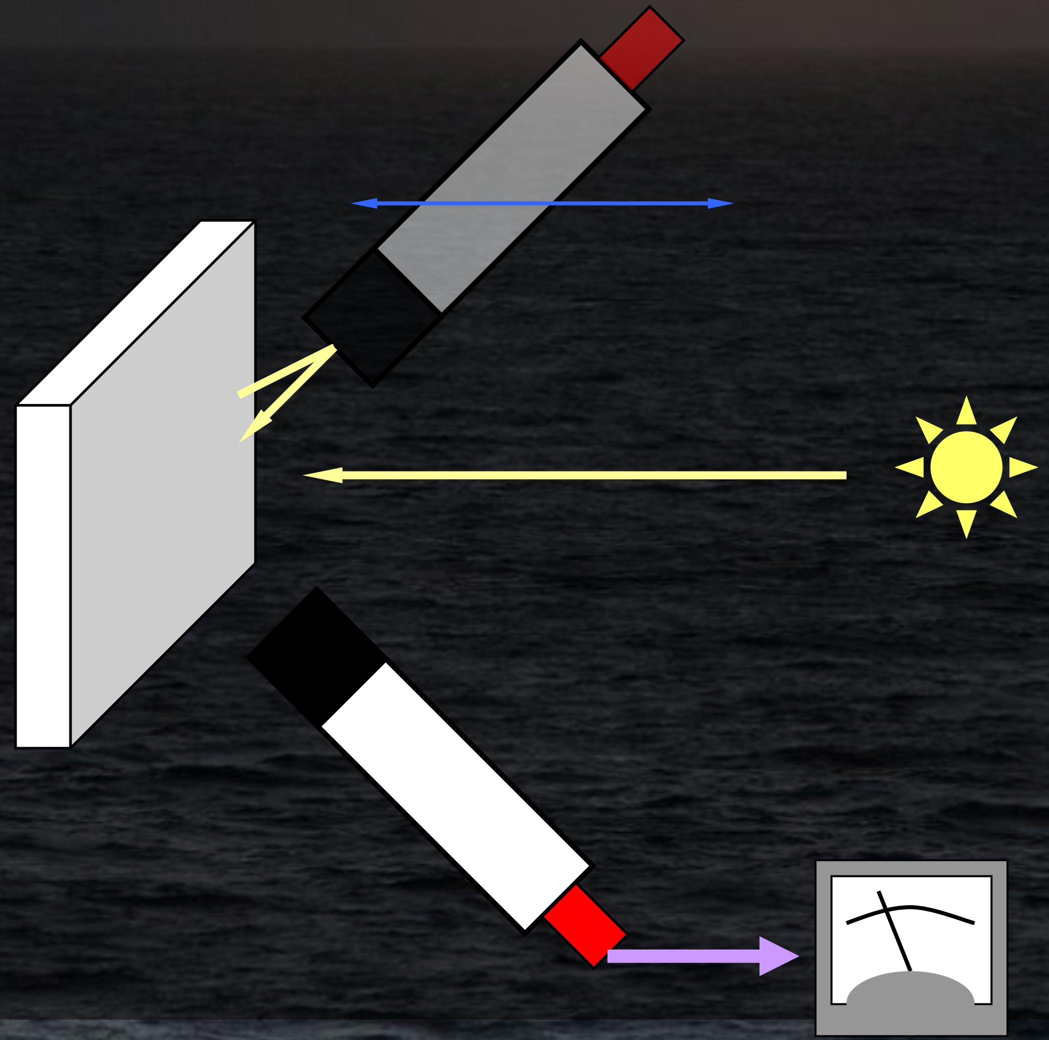
Ambient and internal temperatures

Temperature affects the dark signal and radiometric responsivity.
Dark drift can be compensated with frequent dark acquisitions.
The radiometer's internal temperature is at least 2 $^{\circ}C$ higher than ambient.
The signal change cannot be linked to any particular temperature reading because of the lags and the distribution between multiple components.
Internal self-heating depends on the acquisition mode (integration time, read-out frequency etc.).
Try to reach thermal equilibrium by running the radiometer with the expected intergation time settings for at least 5 minutes.
In the absence of internal temperature sensor, observe the dark signal.
Always log the ambient temperature.

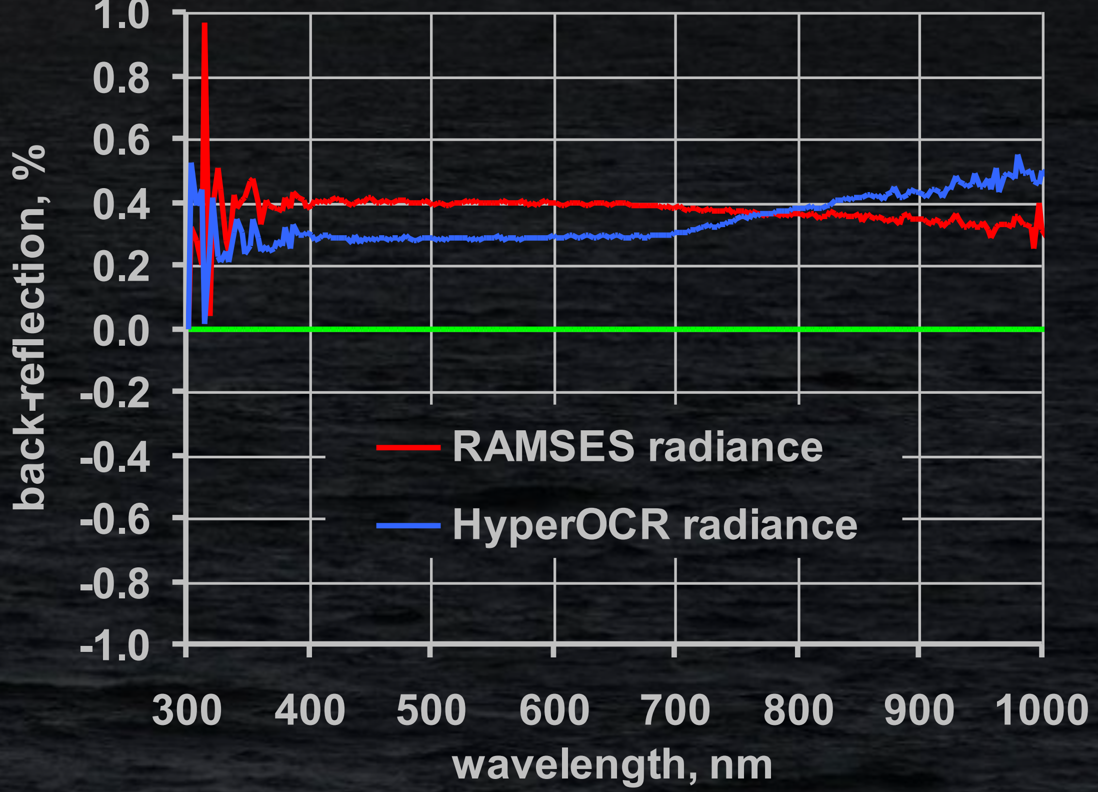
Radiance calibration: back reflection and vignetting



Measuring the back reflection



individual examples



The uncertainty budget

Arising from the calibration source:

lamp & panel calibration certificates
lamp aging
lamp power setting (current measurement, shunt resistance)
lamp & panel interpolation

Arising from the radiometer:

wavelength scale
repeatability (type A)
temperature, linearity & spectral stray light

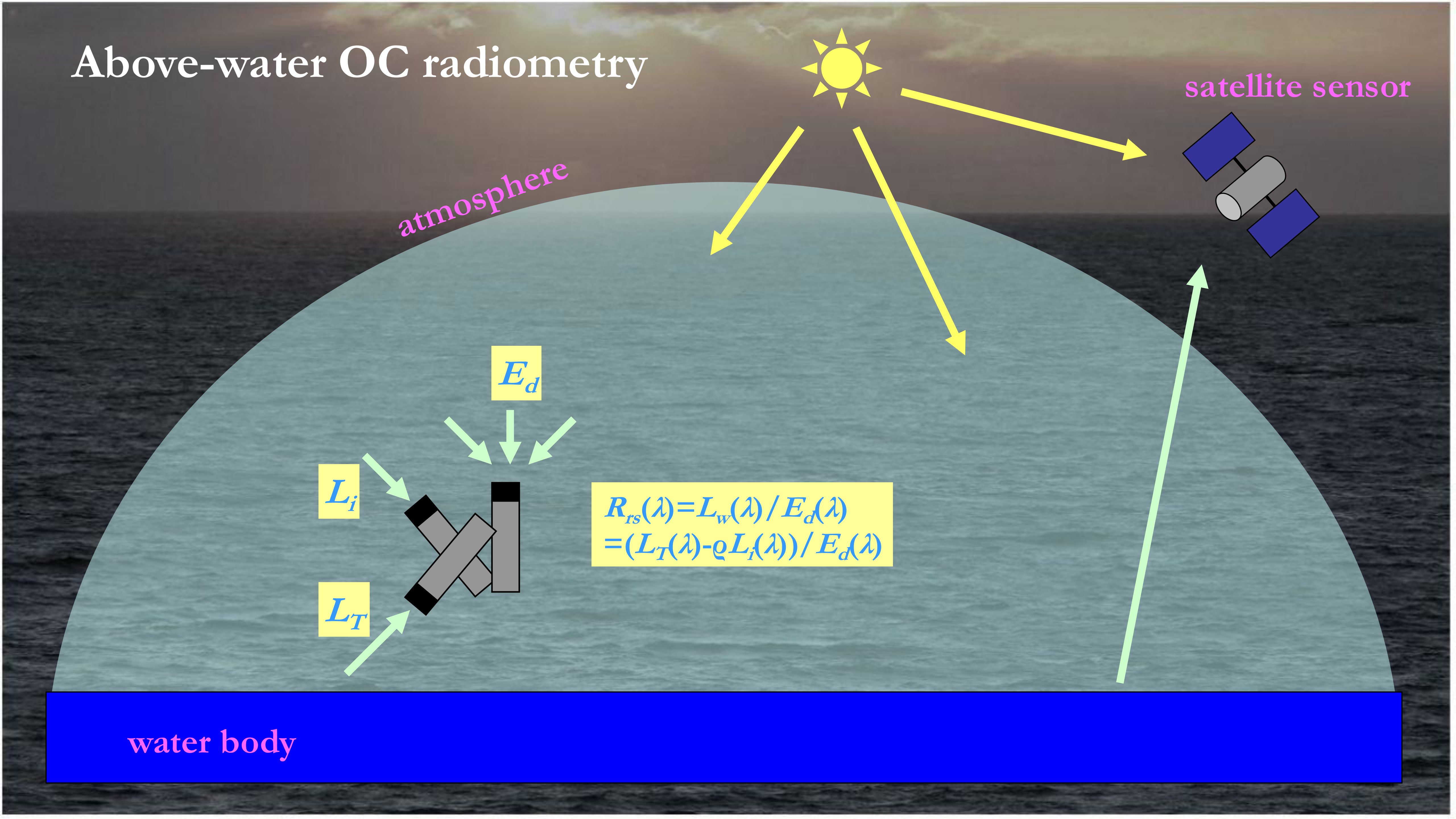
Arising from the method:

distance setting
lamp & panel alignment
ambient stray light
reproducibility

Next steps

The following (and more) remaining issues are related to the differences between the lab and the field conditions, affecting the SI-traceability of the field measurements, and need further investigation.

- Effective reference plane & aperture of the irradiance input
- Effective reference plane of the panel (not affecting sphere setups)
- Recommended distance between the lamp and the panel
- Recommended distance between the panel and the radiance sensor (related to the back-reflections, FOV & vignetting)
- Quantifying the back-reflections (they do not happen in field conditions)


Above-water OC radiometry
satellite sensor
atmosphere
E_d
L_i
L_T
$R_{rs}(\lambda)=L_w(\lambda)/E_d(\lambda)$
$=(L_T(\lambda)-\rho L_i(\lambda))/E_d(\lambda)$
water body

Calibration uncertainty of R_{rs} in the correlated case

Simplified measurement equation for R_{rs} with correlated calibrations:

$$R_{rs} = \frac{L_T - \rho L_i}{E_d} = \frac{\frac{Sraw}{Scal}\pi \cdot \cancel{Lamp} \cdot Panel - \rho \frac{Sraw}{Scal}\pi \cdot \cancel{Lamp} \cdot Panel}{\frac{Sraw}{Scal}\cancel{Lamp}}$$

$$\dashrightarrow u(R_{rs})$$

Uncertainty of the remote sensing reflectance will be reduced due to the correlation between L_T, L_i and E_d.

Only possible when using the same lamp for the L and E sensors within a short timeframe.

Need to log lamp serial number and calibration times.

Summary

If possible, keep the calibration conditions (angular and spectral distributions, integration times, temperature) close to the field conditions.

Let the radiometers heat up for at least 5 min before the calibration measurements during which keep acquiring spectra with expected integration time.

Do not use automatic integration time settings. Choose the longest applicable integration time so that the signal level is 25000..55000 ADU.

If possible, record exact timestamps & temperatures.

Measure the dark signal temporarily as close as possible to the target spectrum and with the same integration time.

Provide raw calibration data for further processing by the users.

Build the uncertainty budget!