Characterization guidelines

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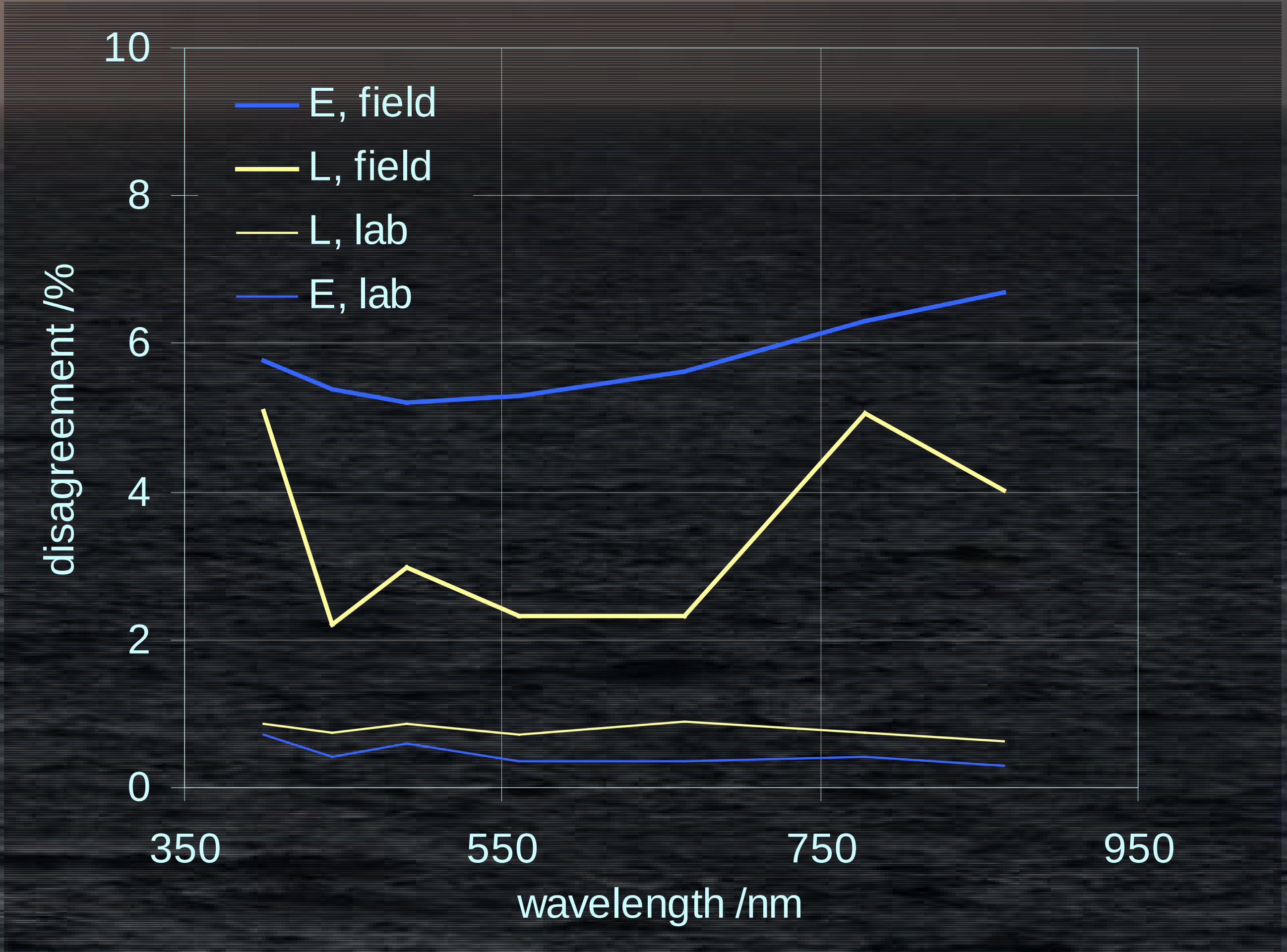
Tõravere 2025

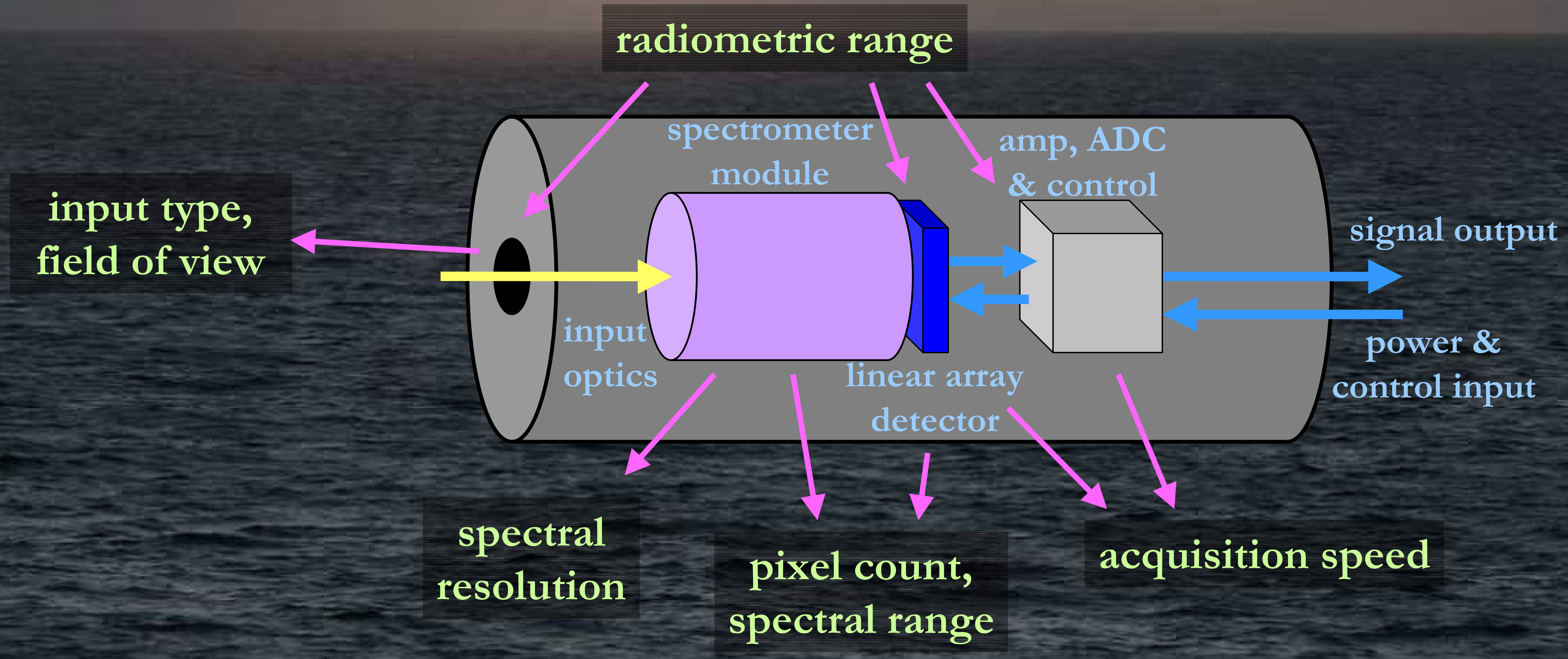
On the importance of characterization

During the FRM4SOC LCE2 experiment, freshly calibrated radiometers were taken to the field to measure radiance and irradiance of sky and water.

Conclusion: radiometric calibration alone is not sufficient, we need characterization as well.



Instrumental parameters



Other: temperature range, power consumption, waterproofness, weight, dimensions, cost, software options ...

Instrumental properties

These properties interfere with the measurement conditions (spatial and spectral distributions and intensity of the light, temperature), affecting the SI-traceability:

radiometric responsivity & long term stability
radiometric non-linearity
wavelength scale
spectral straylight
thermal sensitivity
angular response
polarization sensitivity

... and more:

accuracy of integration times
temporal response
immersion factors
pressure effects

Characterization and correction

Characterization is determination of the optoelectronical, mechanical and environmental properties of the radiometer.

Characterization takes place mostly in the laboratory by using dedicated light sources, environmental conditions and measurement procedures.

Characterization result: a correction factor or formula with uncertainty. This result <u>belongs to the radiometer regardless of the measurement task</u>.

The uncertainty of the <u>characterization result</u> depends on the capabilities of the radiometer and the <u>characterization method</u>.

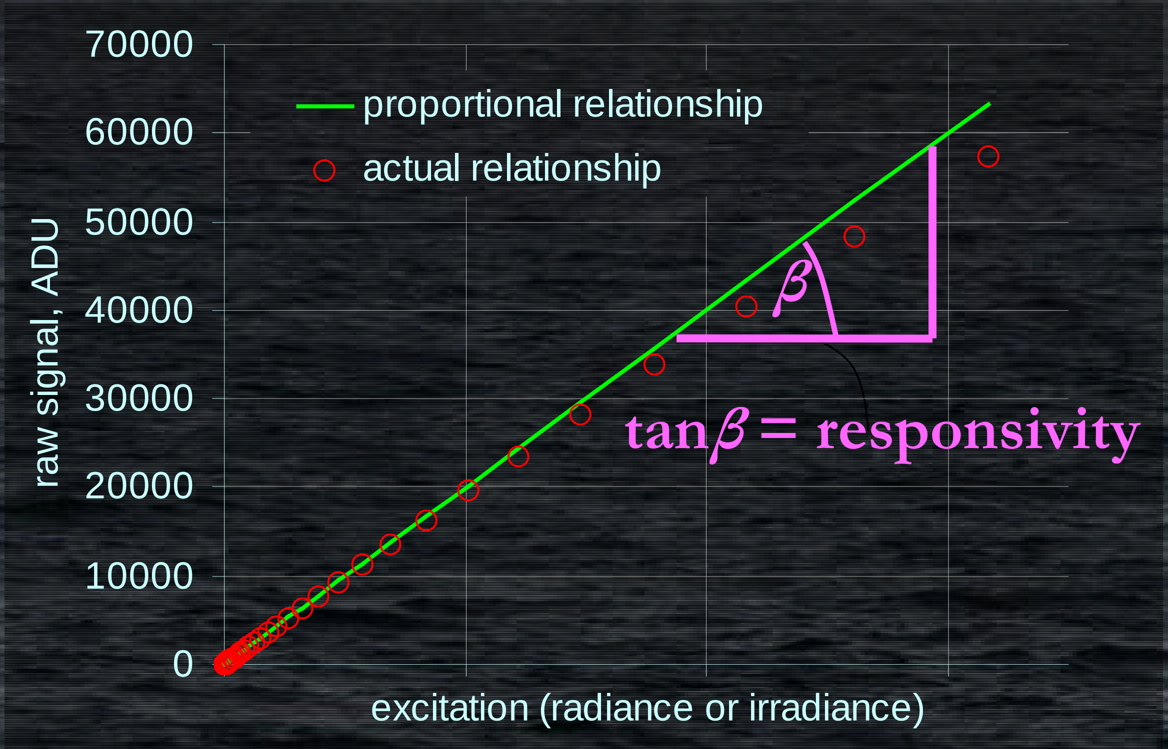
The characterization result is used to correct <u>any</u> (laboratory or field) measurement carried out with the radiometer.

The characterized instrumental property will <u>interact</u> with the measurement conditions: the spectral and angular distribution and intensity of the radiation, temperature etc.

The <u>magnitude and the residual uncertainty of the final correction</u> depend on these conditions.

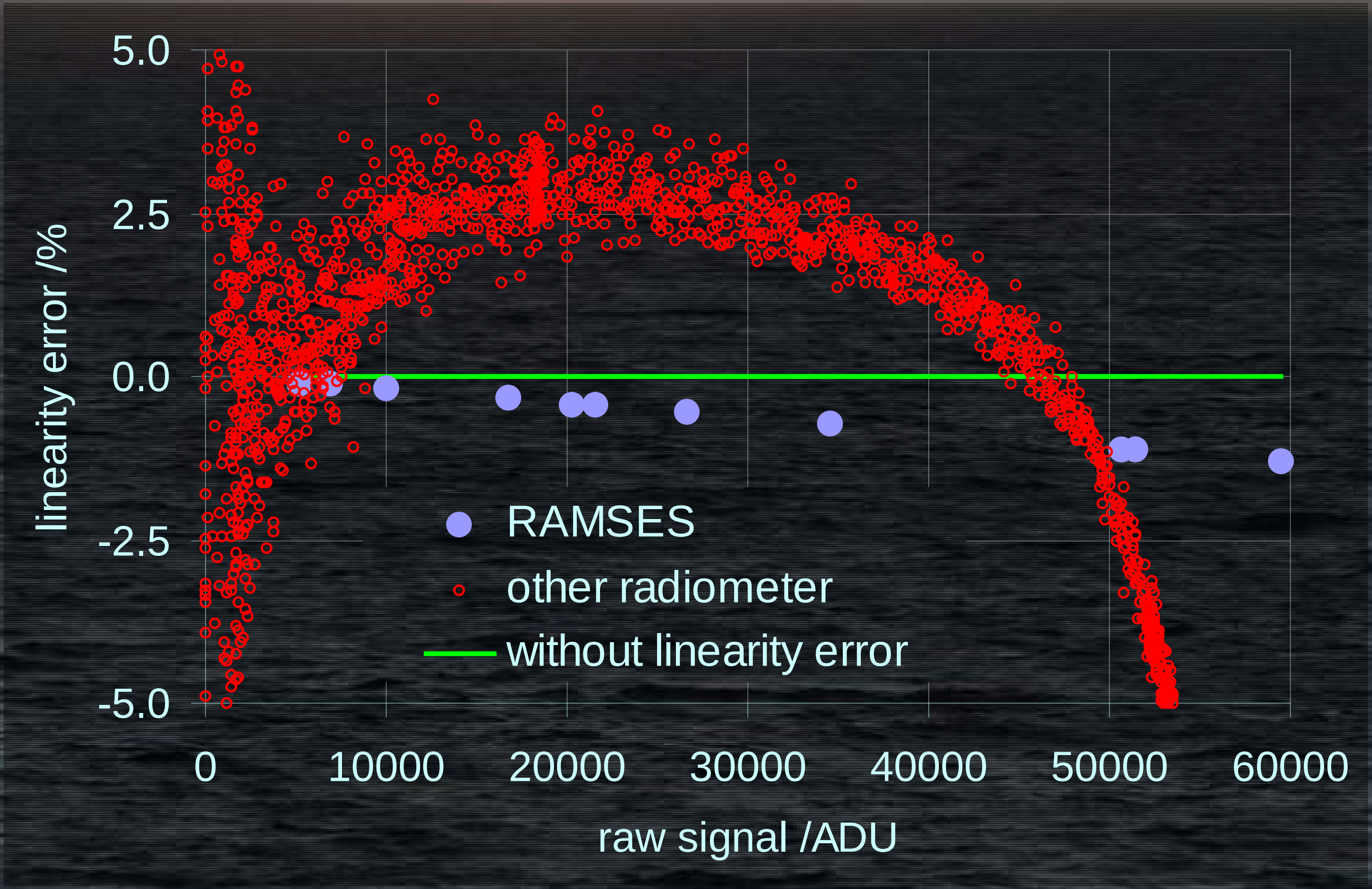
Radiometric non-linearity

Ideal case: output signal* of the radiometer is proportional to the excitation.
Reality: deviation from proportionality, usually at higher signal levels.



*Dark is subtracted

Radiometric non-linearity examples



Measuring the radiometric non-linearity

For characterization of the radiometric non-linearity we need a signal source with precisely controlled variable intensity:

the varying distance method

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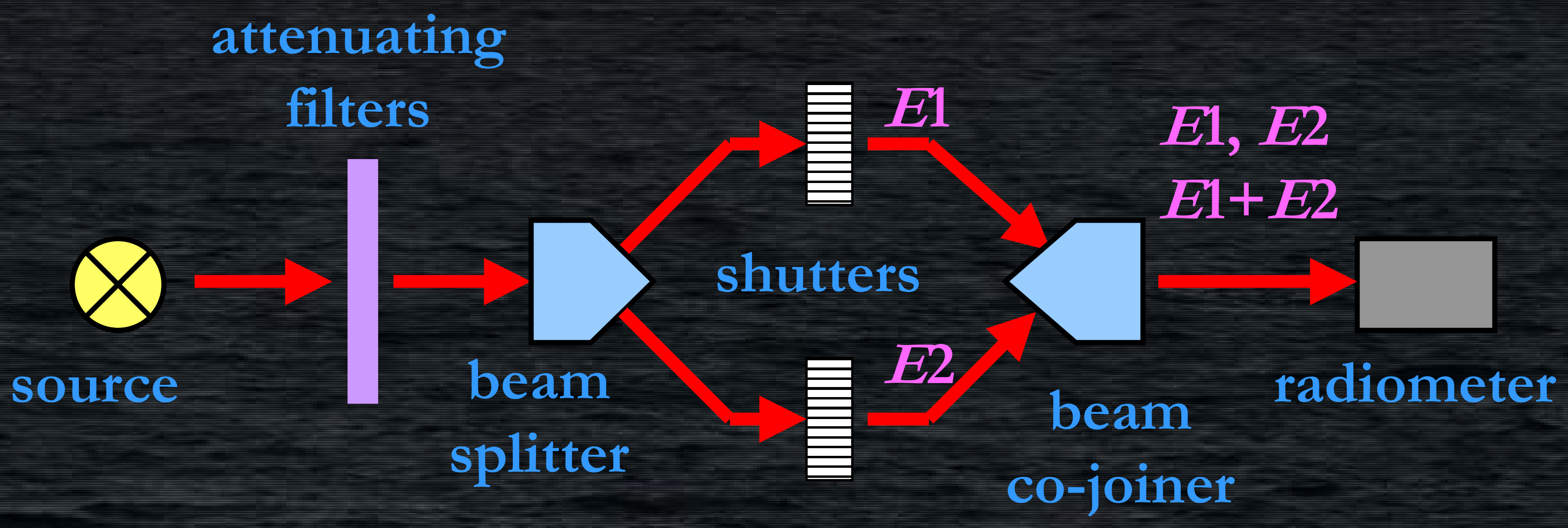


the beam addition method

Radiometric non-linearity

Output raw signal* of the radiometer is proportional to the integration time.
We can replace the varying excitation with varying output signal level
by using different integration times.
The integration time ratios need to be precise.

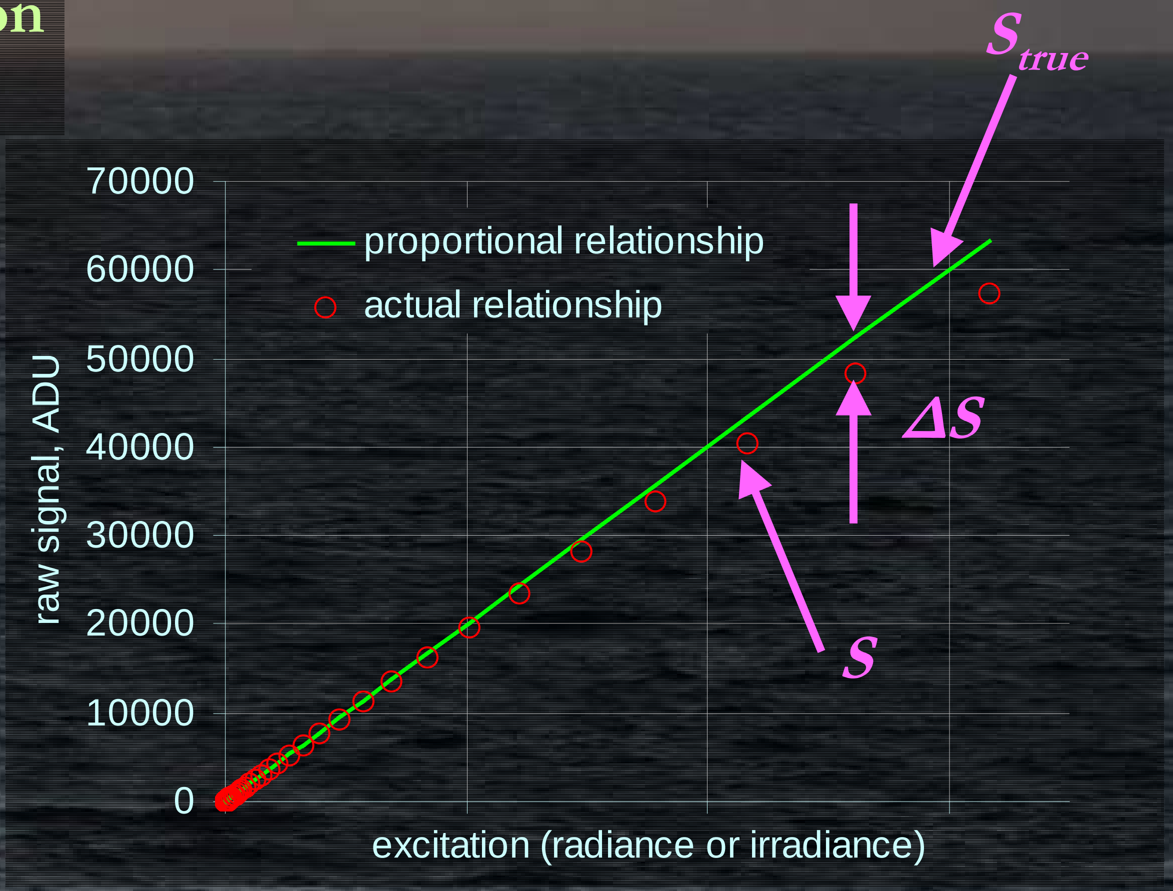
*Dark is subtracted

Radiometric non-linearity

Empirical relationship, proposed by V. Vabson during the FRM4SOC Phase 1 project:

$$\frac{\Delta S}{S_{true}} = \frac{S - S_{true}}{S_{true}} = \alpha \cdot S_{true}$$

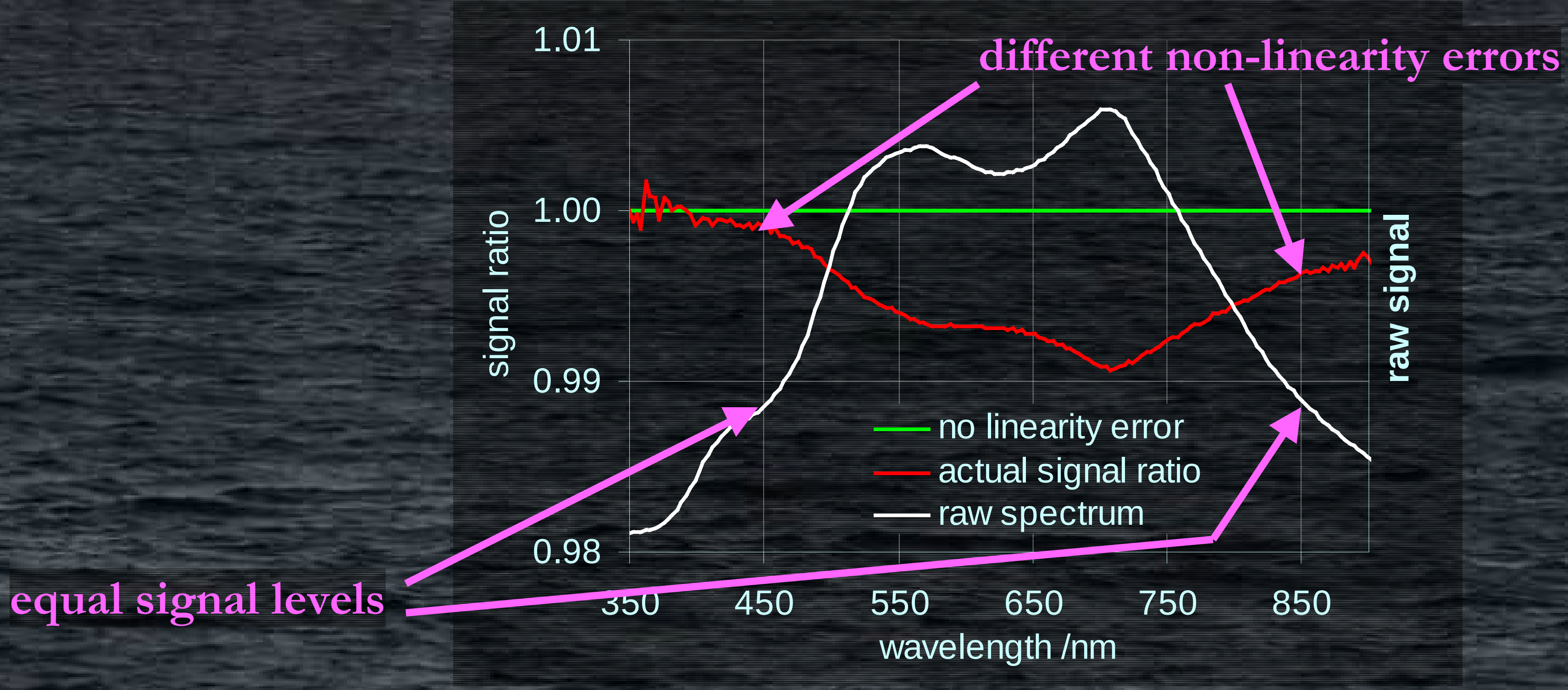
Valid for RAMSES and HyperOCR according to experimental results.



Radiometric non-linearity

The nonlinearity can be easily demonstrated when measuring a stable source with different integration times.

The non-linearity error for RAMSES and HyperOCR dependes on the wavelength.

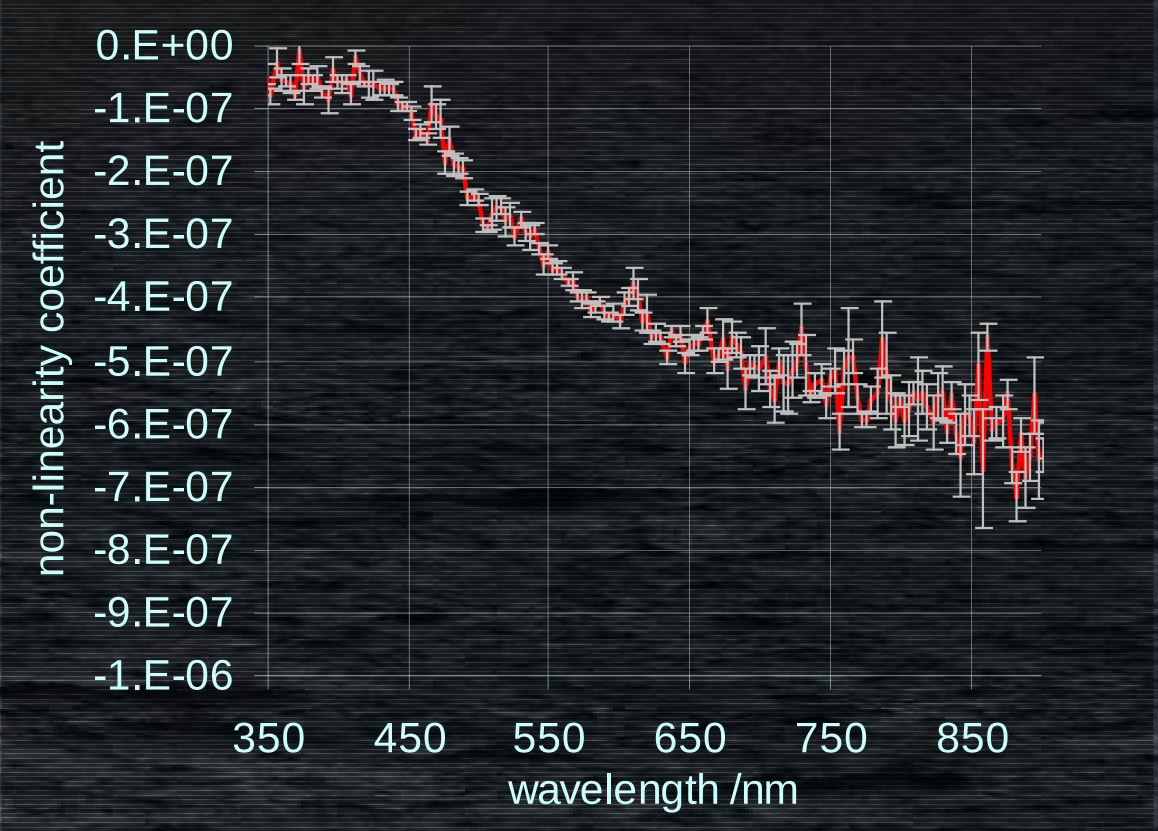


Derivation of the non-linearity coefficient

Calibration source is measured with two integration times *t1* and *t2*:

$$\begin{cases} \dfrac{S(t1)-S_{true}}{S_{true}} = \alpha \cdot S_{true} \\ \dfrac{S(t2)-S_{true}}{S_{true}} = \alpha \cdot S_{true} \end{cases}$$

Will be solved for S_{true} and α,
both depend on the wavelength.
The non-linearity method is cross-validated with the beam addition method and compared to results from JRC.



Non-linearity reporting and uncertainty

The correction and uncertainties are performed by HyperCP.

The calibration lab should provide raw signals (dark subtracted) at two different integration times with corresponding standard deviations. The lamp drift during measurements up to 0.1 % is counted for. The results are reported in the 'CP_*_RADCAL_*.txt' files.

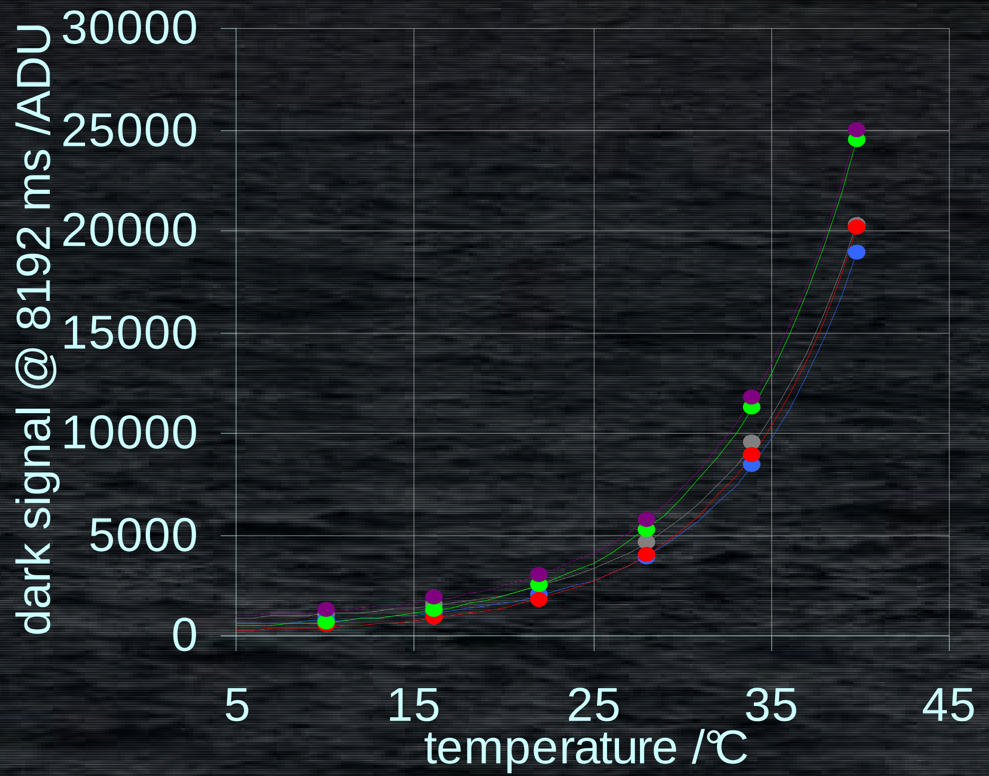
Acquire the series of ~30 spectra with two integration times immediately after each other to meet the expected thermal drift limits.

Dark signal

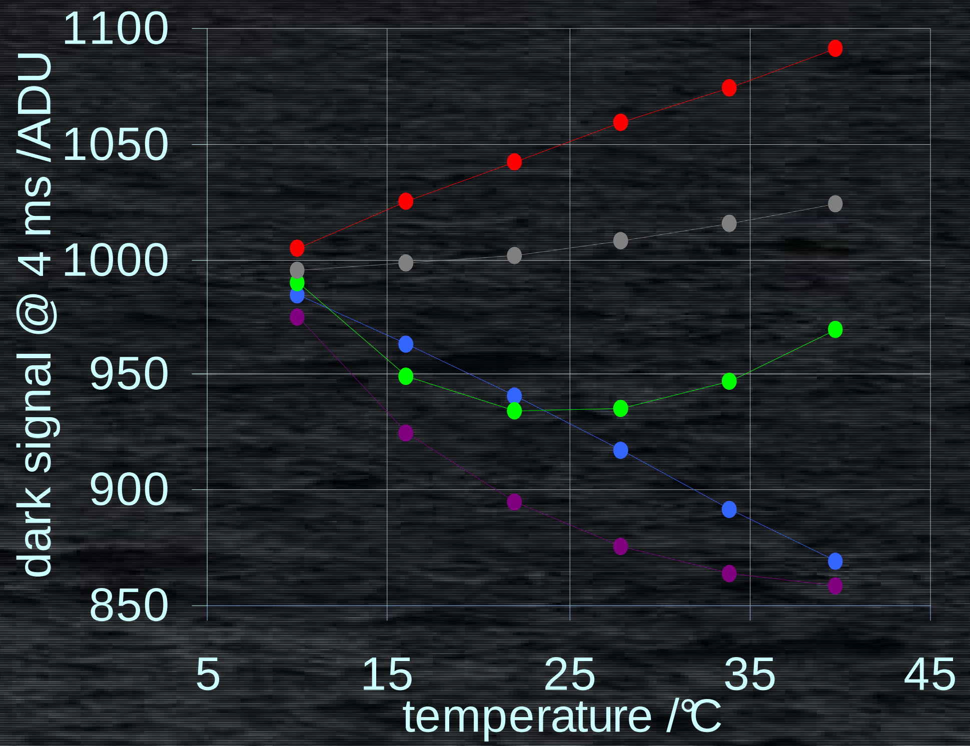
Dark signal depends on the temperature and the integration time.
Dark signal shall be subtracted from the target signal
before any further processing.
Dark signal shall be measured as close as possible to the target signal
and with the equal integration time.
Usage of the stored or modelled dark signals is not recommended.
Dark signal can be used to derive the radiometer's internal temperature.
Dark signal can be used to detect misbehaviour: shutter failure,
noisy output signal, electromagnetic interference etc.

Dark signal vs. temperature

Photodetector dominates the dark signal at longer integration times. Temperature dependence of the photodiode is typically exponential.

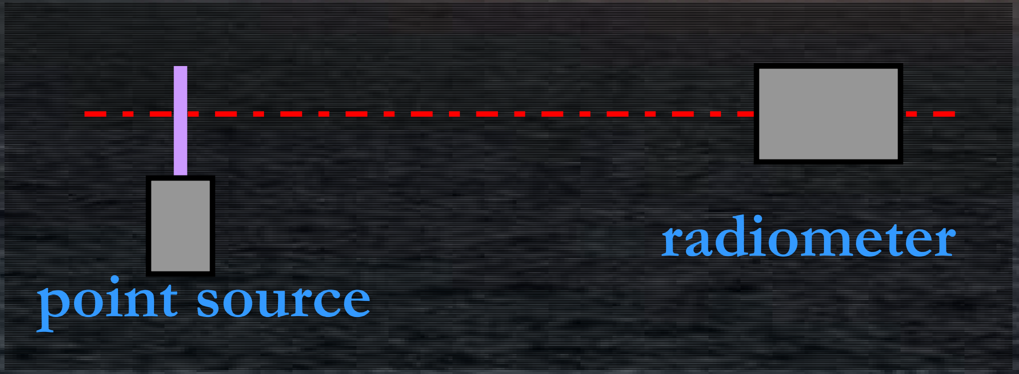


At short integration times, behaviour of the front-end electronics (incl. amplifiers, analog-to-digital converter, voltage references etc.) becomes evident.



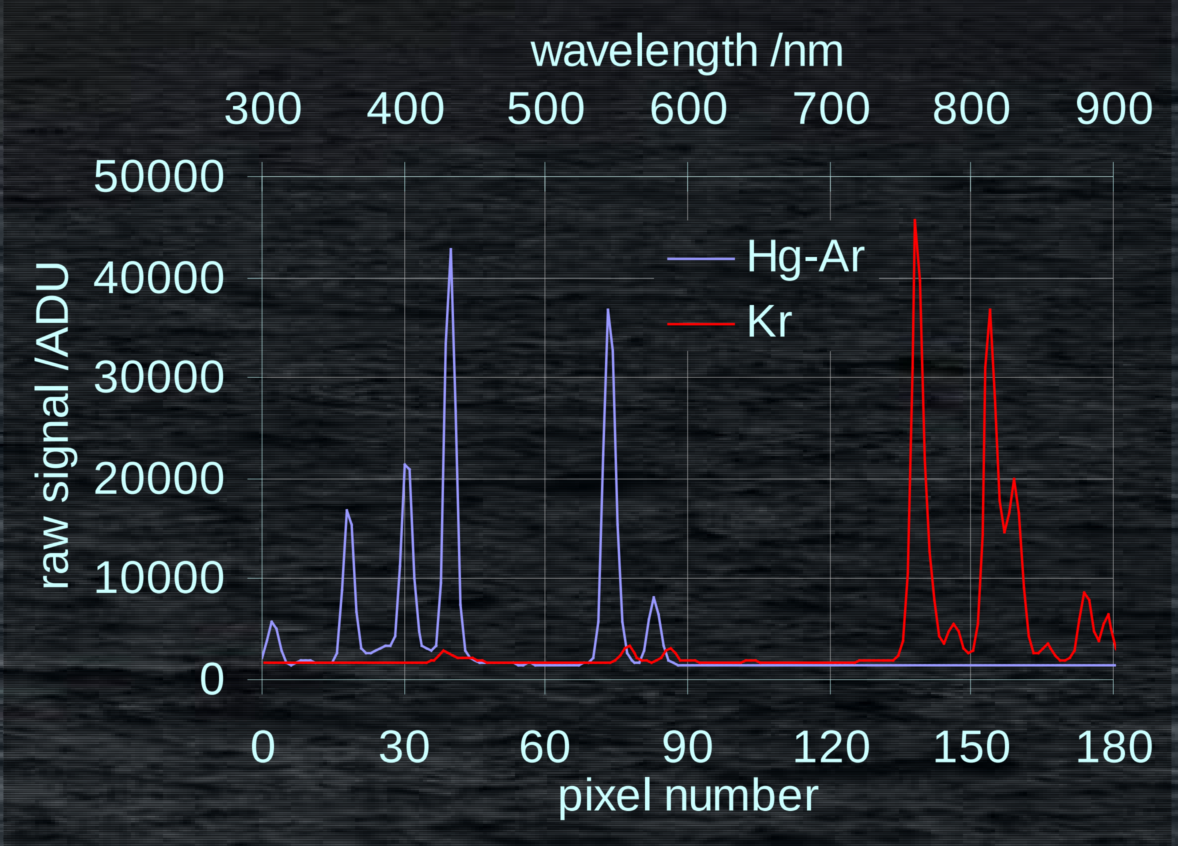
Wavelength scale

Use a spectral line source (discharge lamps, gas laser) to establish relationship between the wavelength and the pixel number.



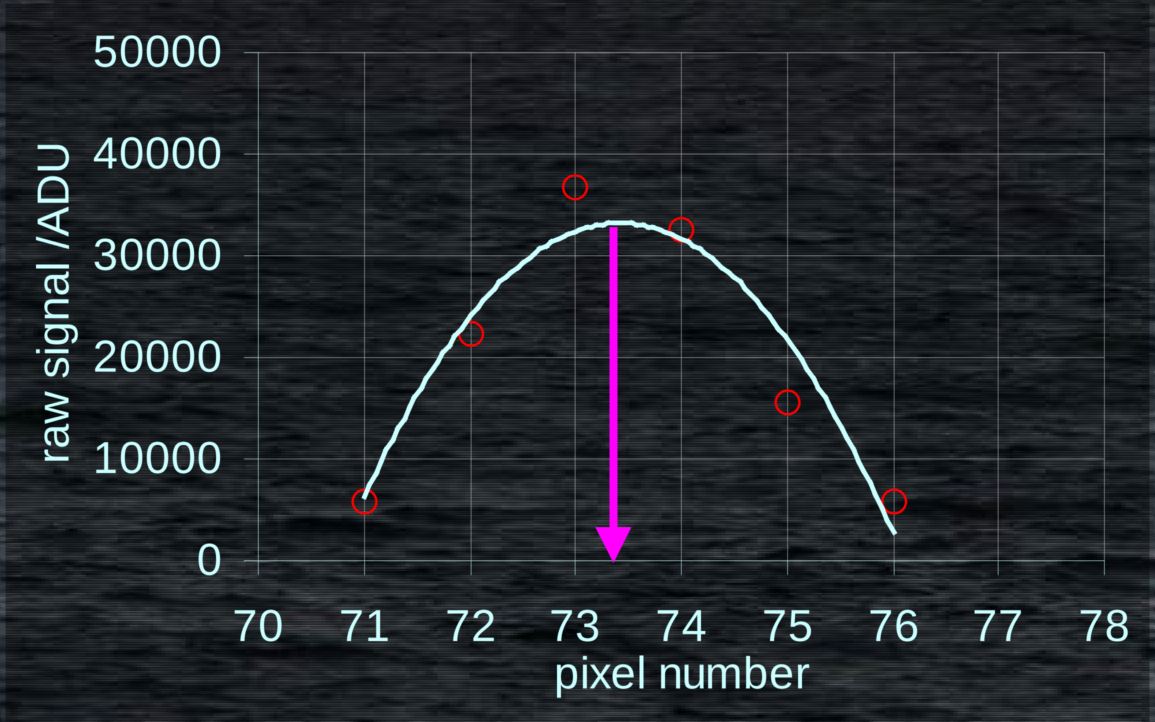
Pen-Ray lamp
(Kr, Ar, Hg, ...)

low pressure
Hg lamp

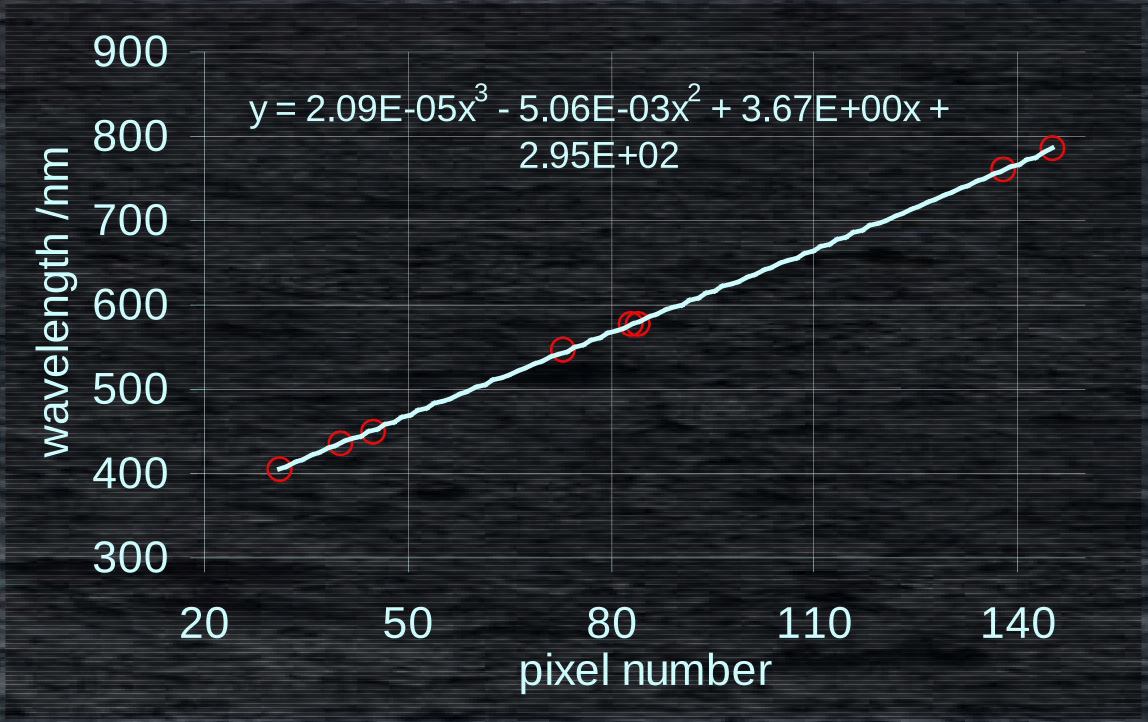


Wavelength scale

Strong lines are detected first, based on the tabulated spectral data.
The peaks are detected with sub-pixel resolution.



A low-order polynomial is used for approximation



Reporting and uncertainty of the wavelength scale

The wavelength scale of RAMSES & HyperOCR is stable between +5 and +40 °C according to TO. Nevertheless, the updated wavelength column can be included in the 'CP_*_RADCAL_*.txt' files.

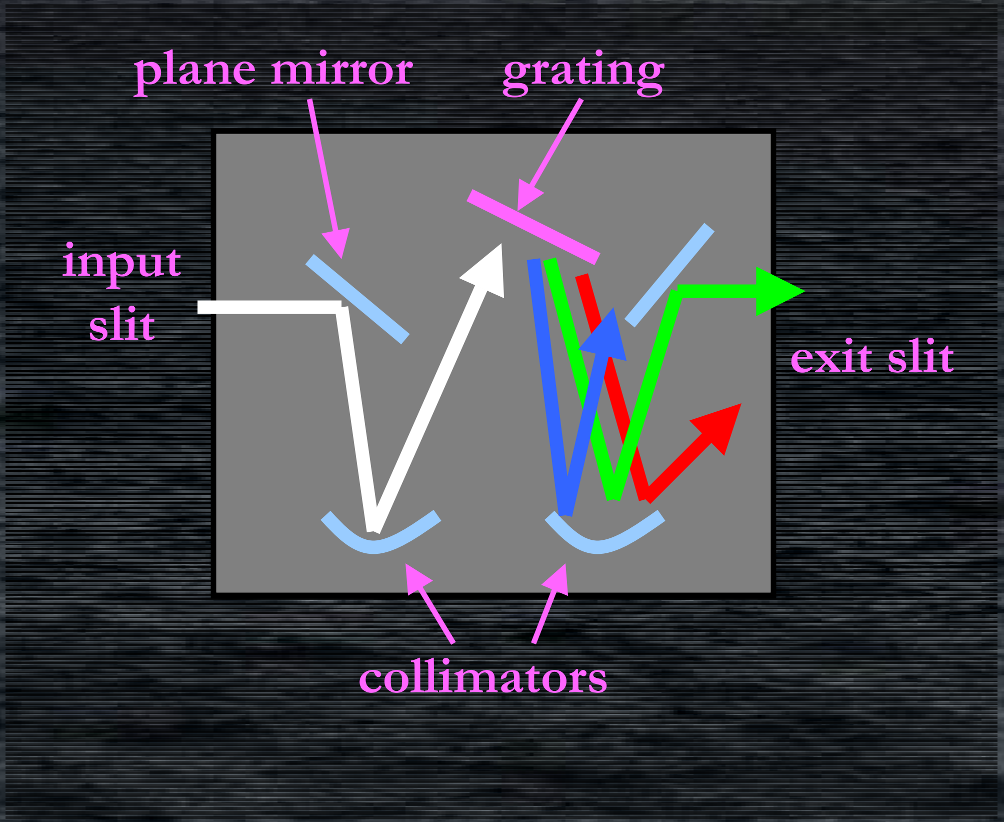
To be included in the uncertainty budget:

repeatability
reproducibility
peak detection accuracy

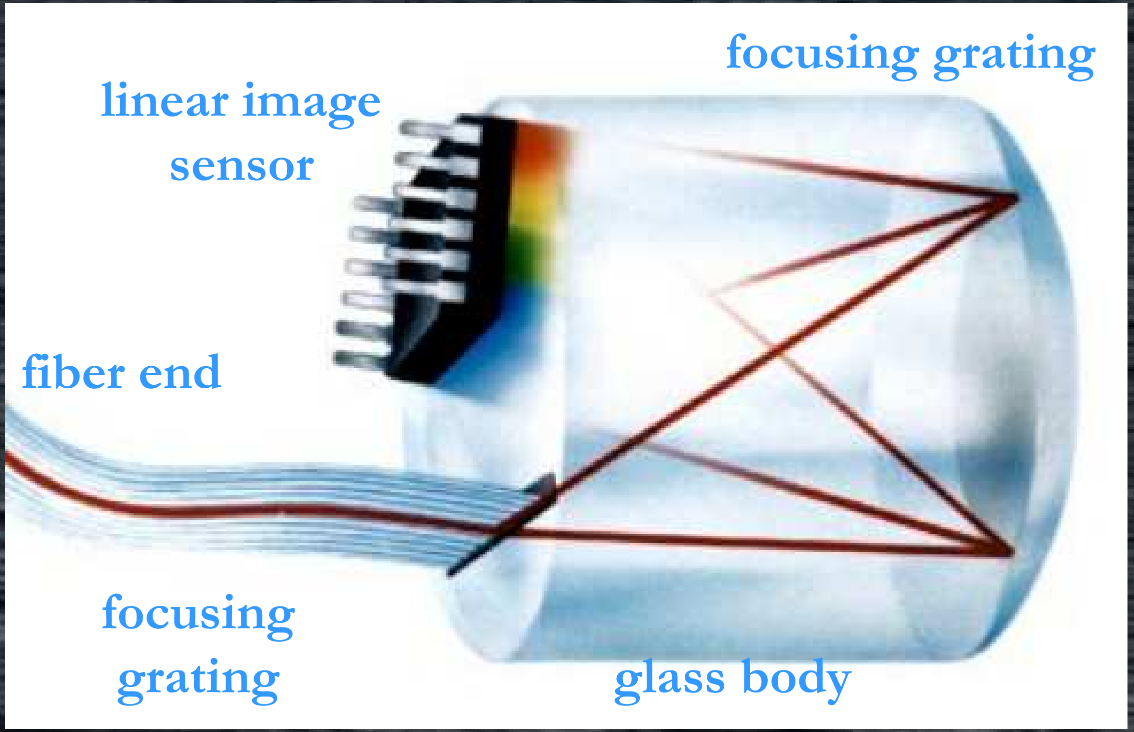
Spectral stray light

Ideal case: each pixel records signal at the pixel's wavelength.
Reality: certain amount of the pixel's signal is caused by other wavelengths.

Monochromator



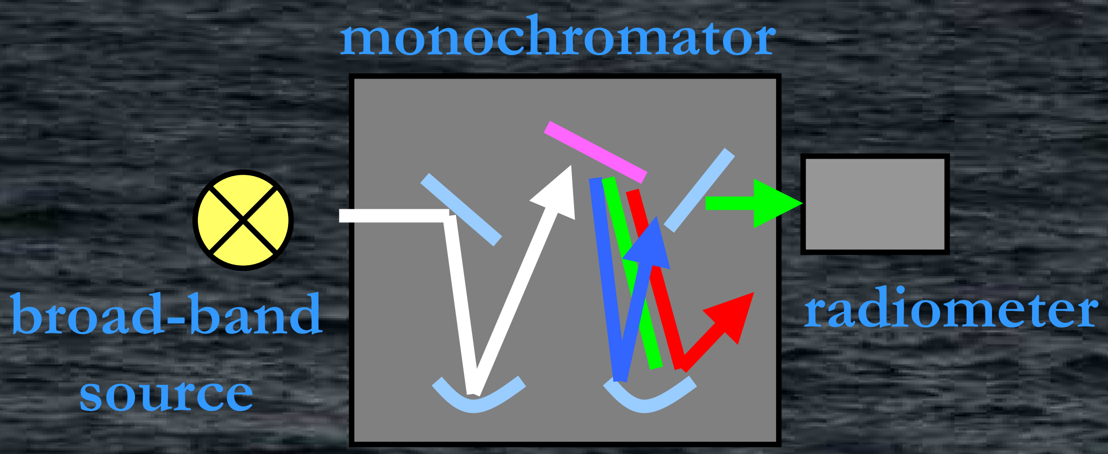
Zeiss MMS1 module



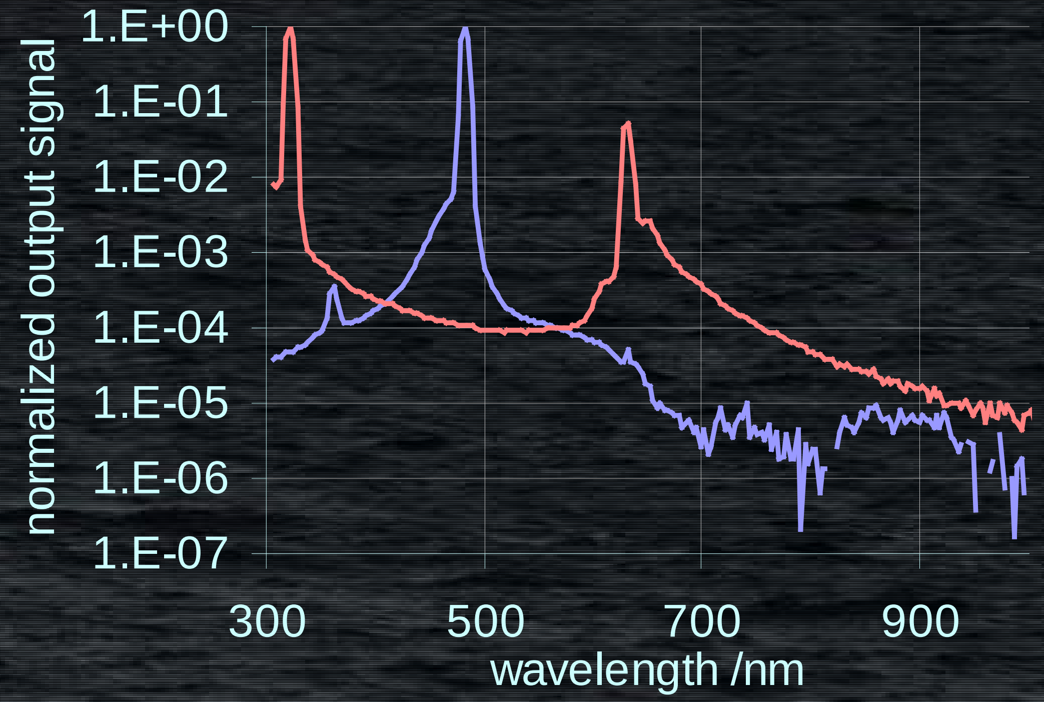
Spectral stray light

For stray-light characterization, a tunable monochromatic source is needed to directly measure the line spread function (LSF) for each pixel.

Tunable lasers or scanning double monochromators can be used.



example LSFs

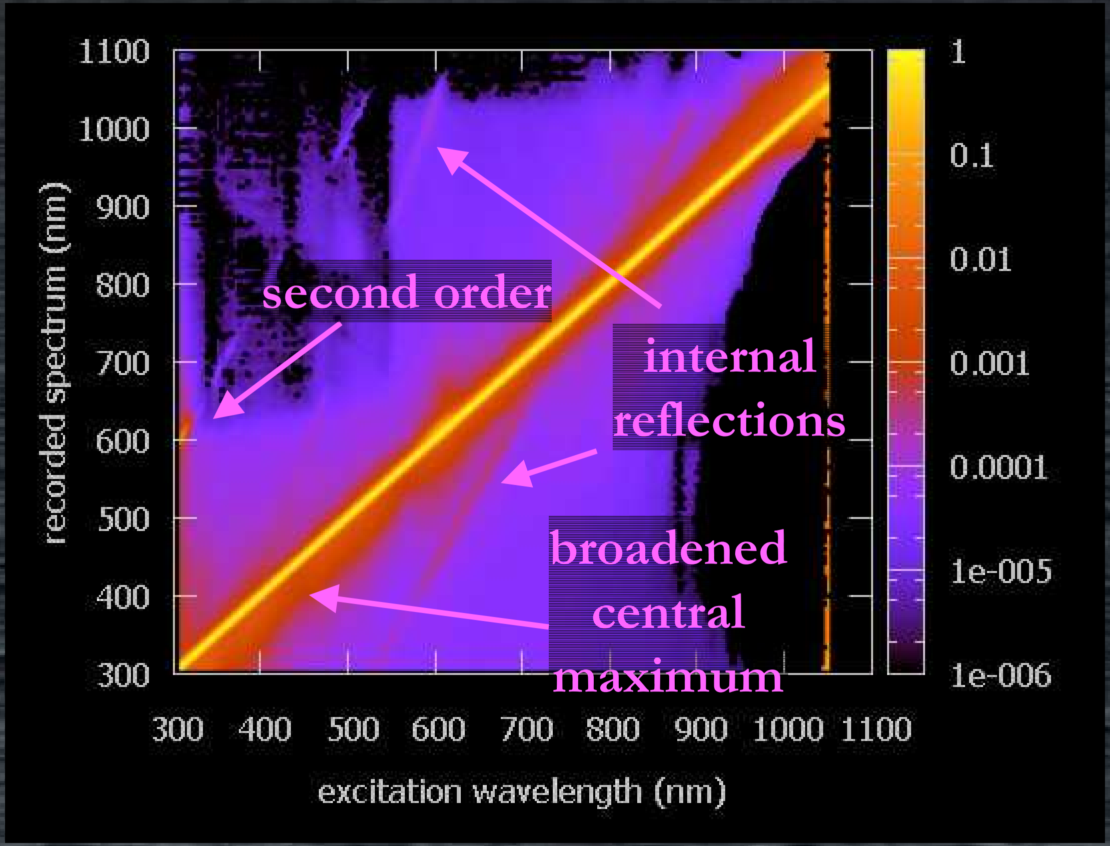


Spectral stray light

Line spread functions (LSF) are combined into stray light matrix (SLM).

LSFs in columns

$$\begin{bmatrix} z_{n0} & z_{n1} & \cdots & 1 \\ \cdots & \cdots & \cdots & \cdots \\ z_{10} & 1 & \cdots & z_{1n} \\ 1 & z_{01} & \cdots & z_{0n} \end{bmatrix}$$



Stray light correction

Stray light matrix is used to correct individual raw spectra.

The calibration source (lamp & panel or sphere) spectra and the raw calibration and field spectra are needed to derive the stray light corrected calibrated field result.

Reporting & uncertainty of the stray light

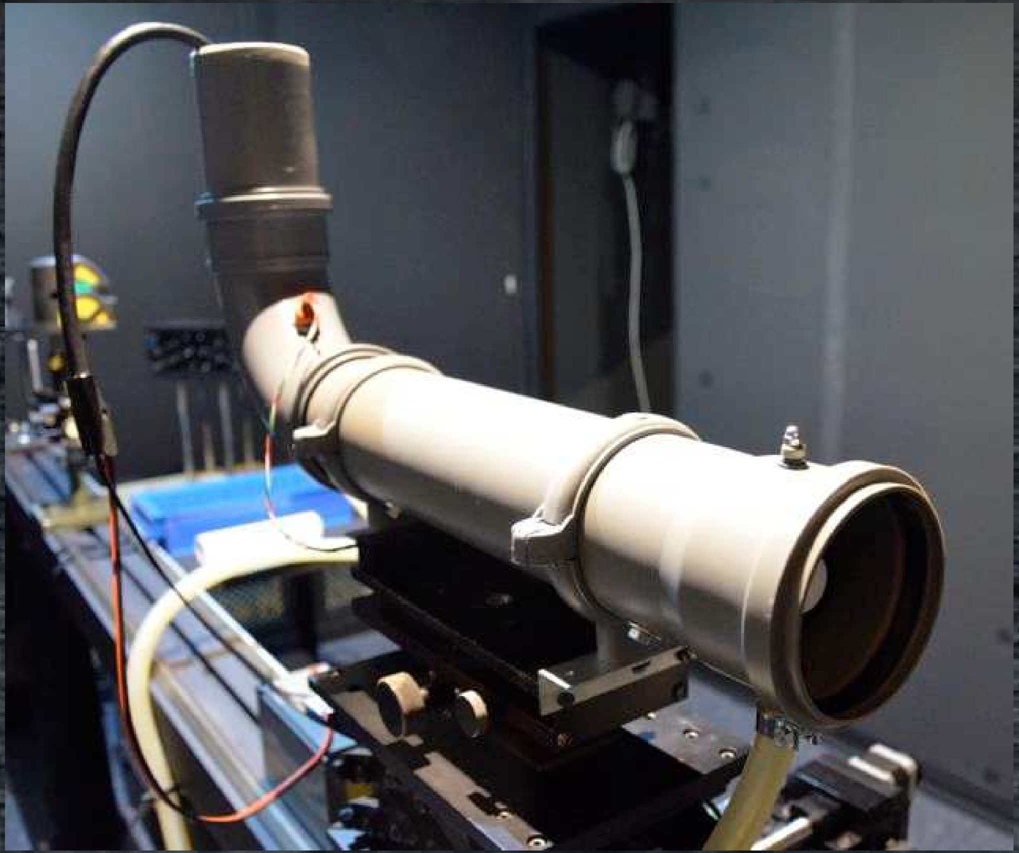
The stray light matrix is reported in the 'CP_*_STRAY_*.txt' files.
Currently, only the standard deviation (i.e. the repeatability) is included.
HyperCP takes care of the further processing.

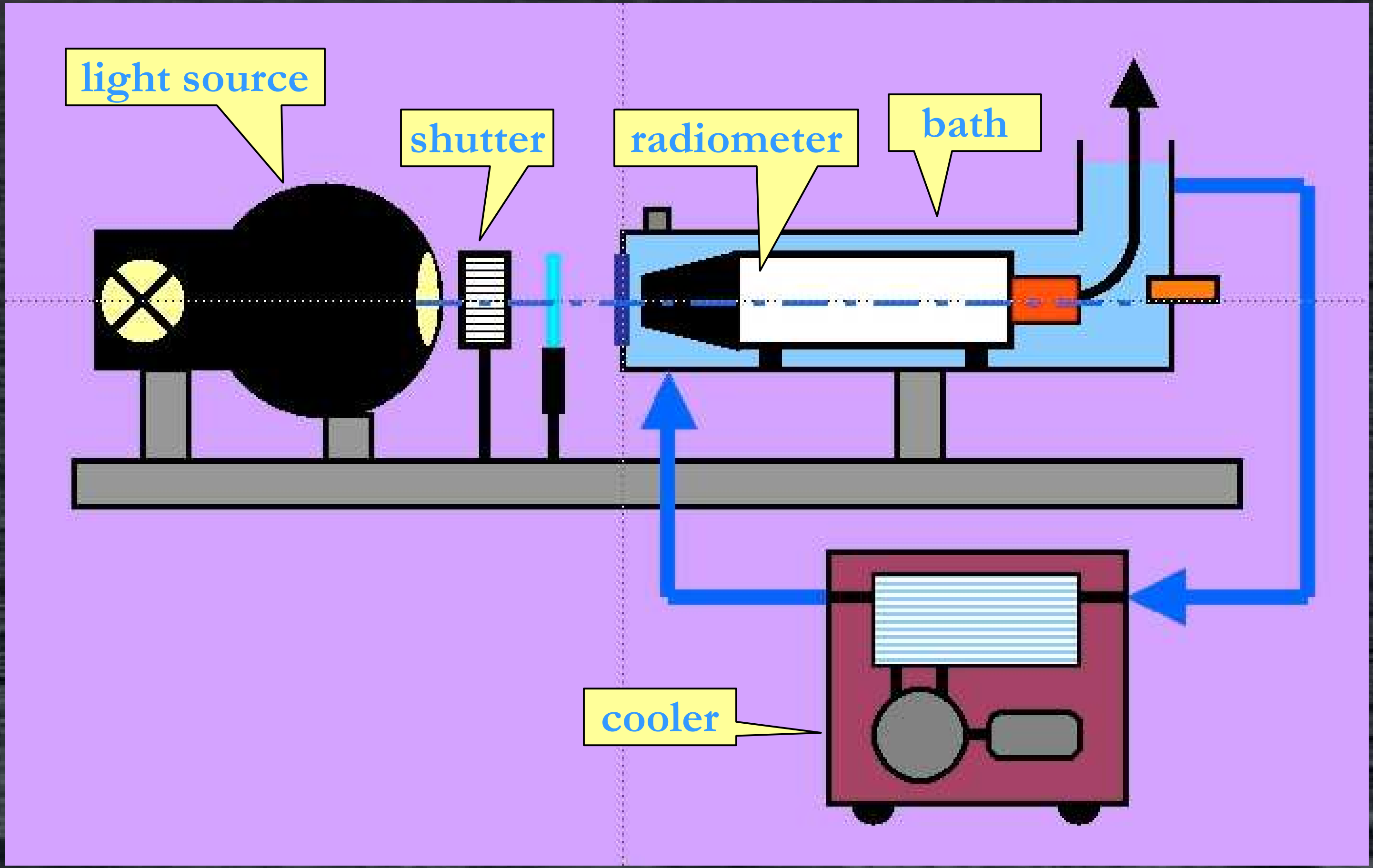
Thermal response

Expected temperature range during the field work is +(2..40) °C.
Most significant are the changes in dark signal and responsivity.
Responsivity change depends on the wavelength.
Measure the dark close to the target signal and with the same integration time.

Measurement setup for thermal characterization

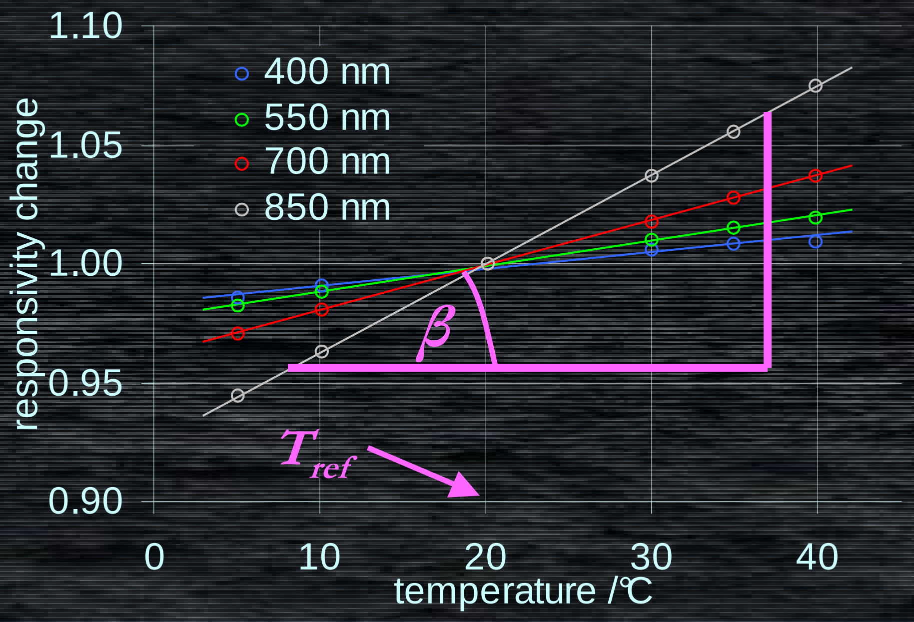
Thermal characterization is a lengthy process: relaxation times of ~1 h are required. This puts high demands on the temporal stability of the source and the alignment.





Thermal characterization method

Measure <u>temporarily stable</u> source at different radiometer temperatures to determine thermal coefficients of the radiometric responsivity.
Combine the experiment with characterization of the non-linearity, dark signal, wavelength scale, polarization sensitivity etc.
Thermal coefficients are evaluated separately for each pixel.
Measurement results are referenced to certain temperature, typically +20 °C.



Thermal coefficient

$c_T(\lambda) = \tan\beta$

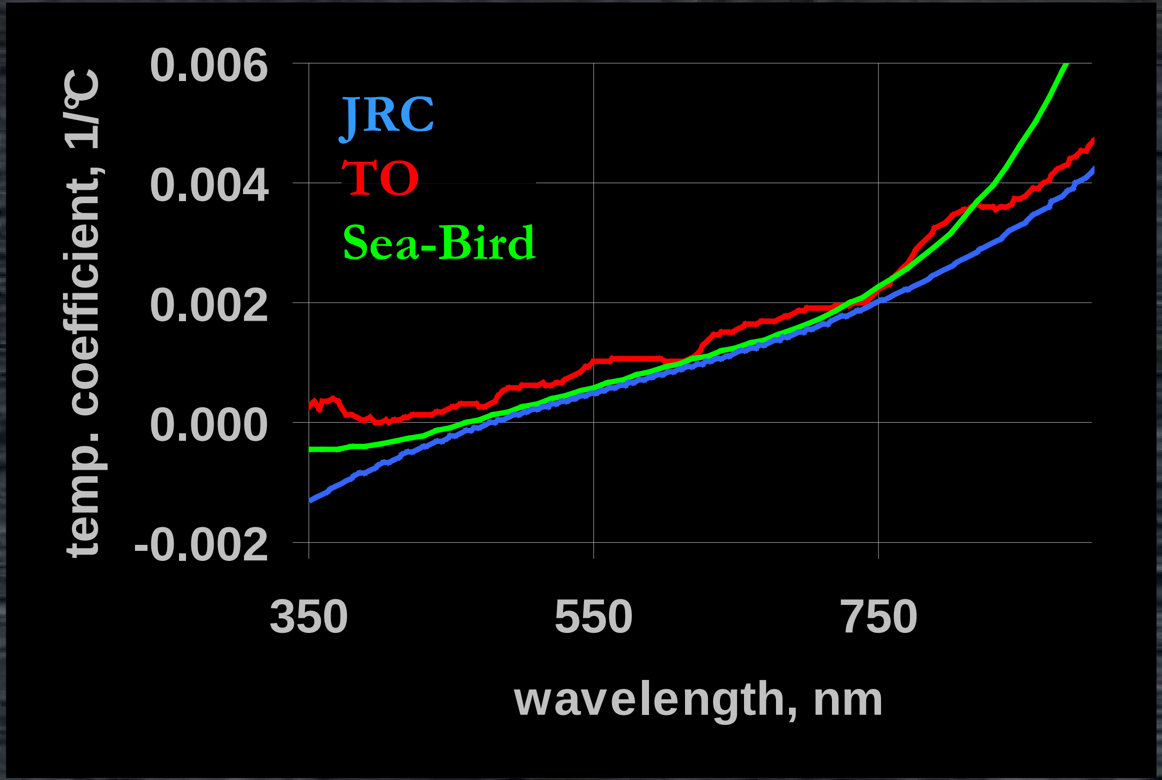
Correcting the field spectra:

$S(\lambda, T_{ref}) = S(\lambda, T)[1 + (T - T_{ref})c_T(\lambda)]$

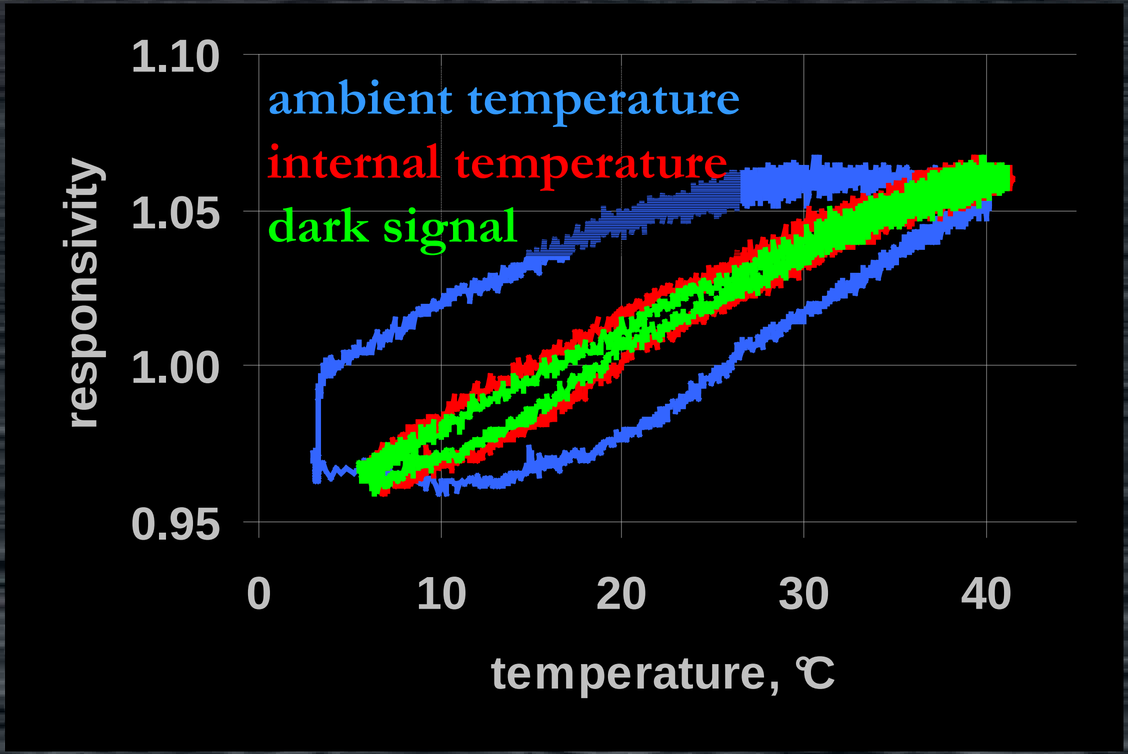
raw or calibrated signal

Thermal response

Validation of the thermal characterization method: TO vs. JRC vs. Sea-Bird.

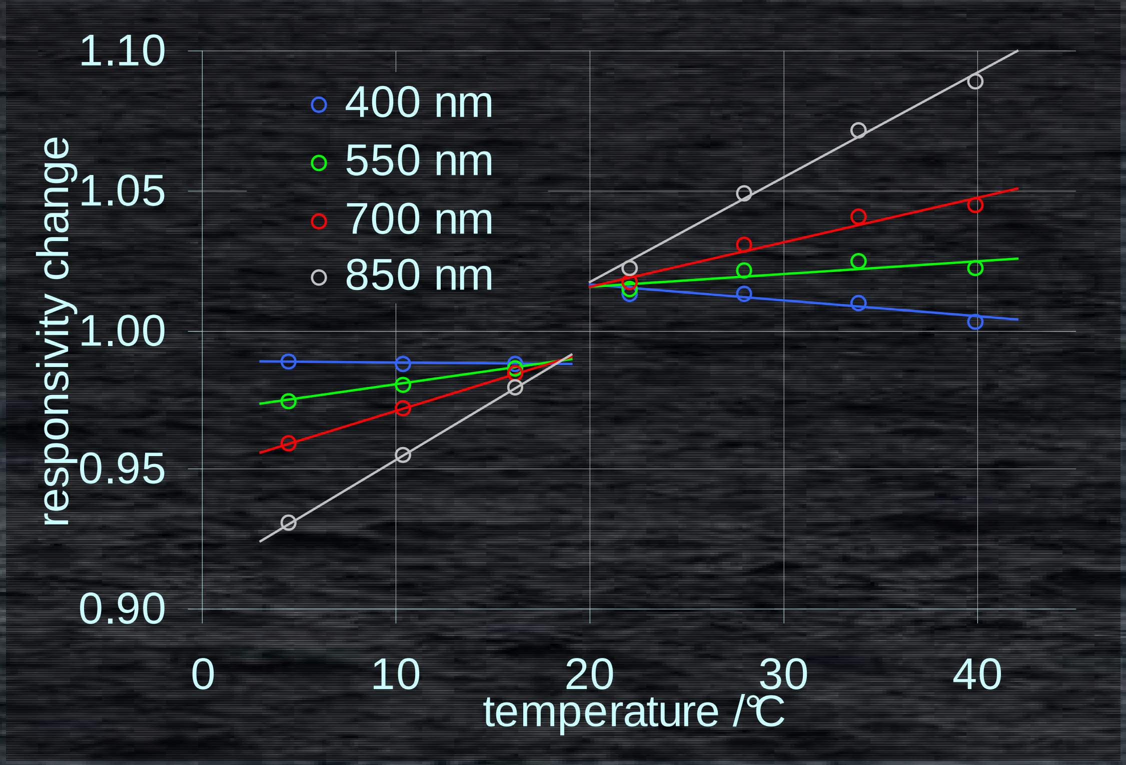


Fast temperature change: temperature sensor signal does not follow the responsivity.
Uncertainty will increase.
Dark signal is a good temperature proxy.

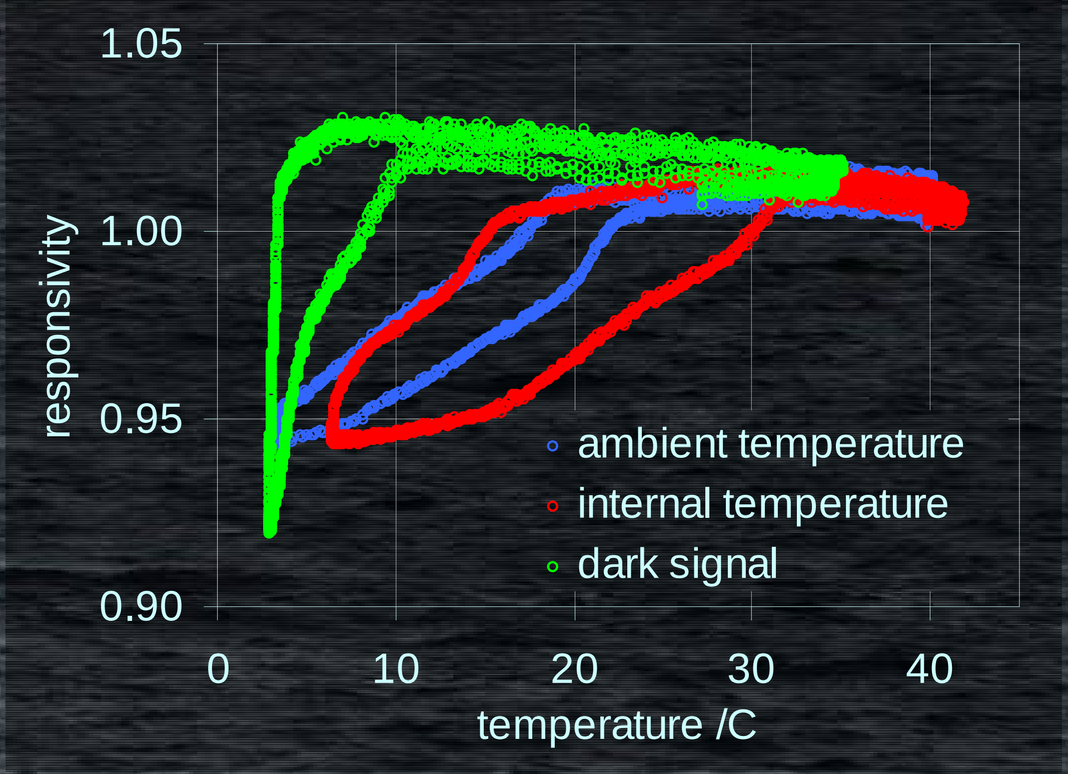


Thermal response: PTFE

Slow temperature change



Fast temperature change



Reporting and uncertainty of the thermal coefficients

$c_T(\lambda)$ with uncertainty are reported in the 'CP_*_THERMAL_*.txt' files.
Perform repeated test experiments with temperature ramps in opposite directions to evaluate the reproducibility and hysteresis contributions.
Also take into account the uncertainties due to the repeatability, lamp drift and regression.

Angular response

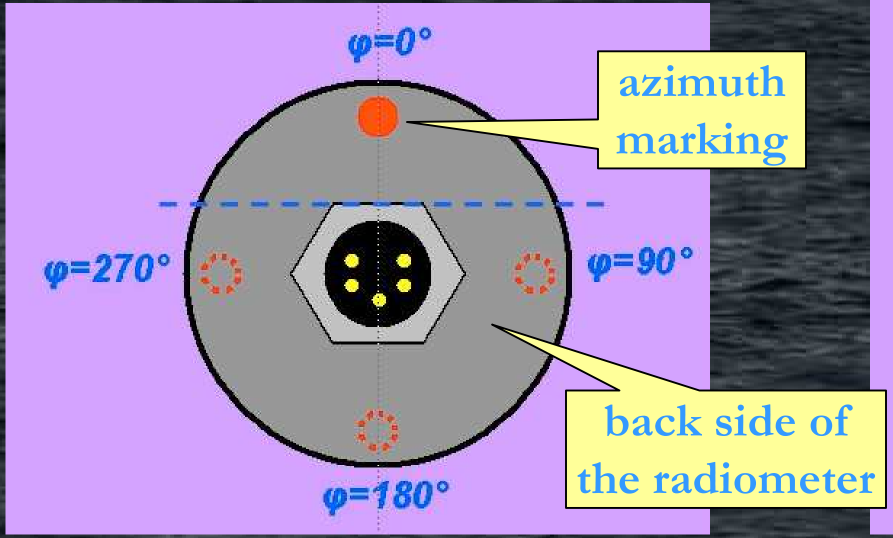
Ideal case (radiance): narrow FOV with flat top and steep edges.
Ideal case (irradiance): angular response follows the cosine law.
Azimuthal symmetry of the response is assumed.

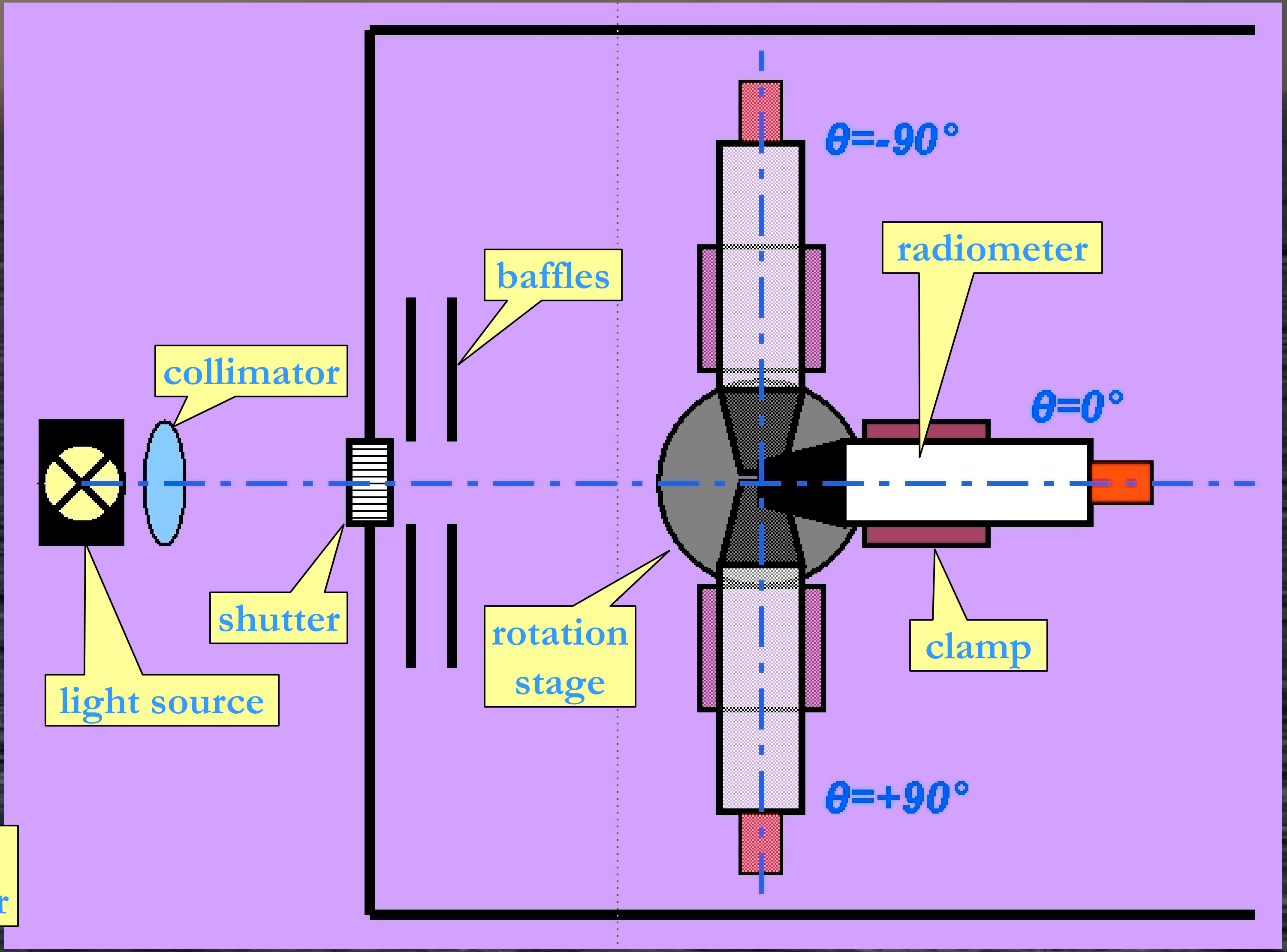
Reality (radiance): non-uniformity within the FOV, gentle slopes.
Reality (irradiance): deviation from the cosine law.
Angular response depends on the principal plane.

Angular response characterization setup

Measurement method: precise rotation of the radiometer within the collimated beam.

Zero azimuth is marked with a red dot on the radiometer's body.





Angular response

Lamp and convex lens (or concave mirror) form a collimated beam.
Incident angle is changed by rotating the radiometer.
Characterization result: normalized responsivity vs. incident angle for each pixel.

Angular response of the irradiance sensors

Ideal case: angular response of the irradiance sensor follows cosine law:

raw or calibrated signal

$$S(\theta,\lambda) = S(\theta=0,\lambda)\cos(\theta)$$

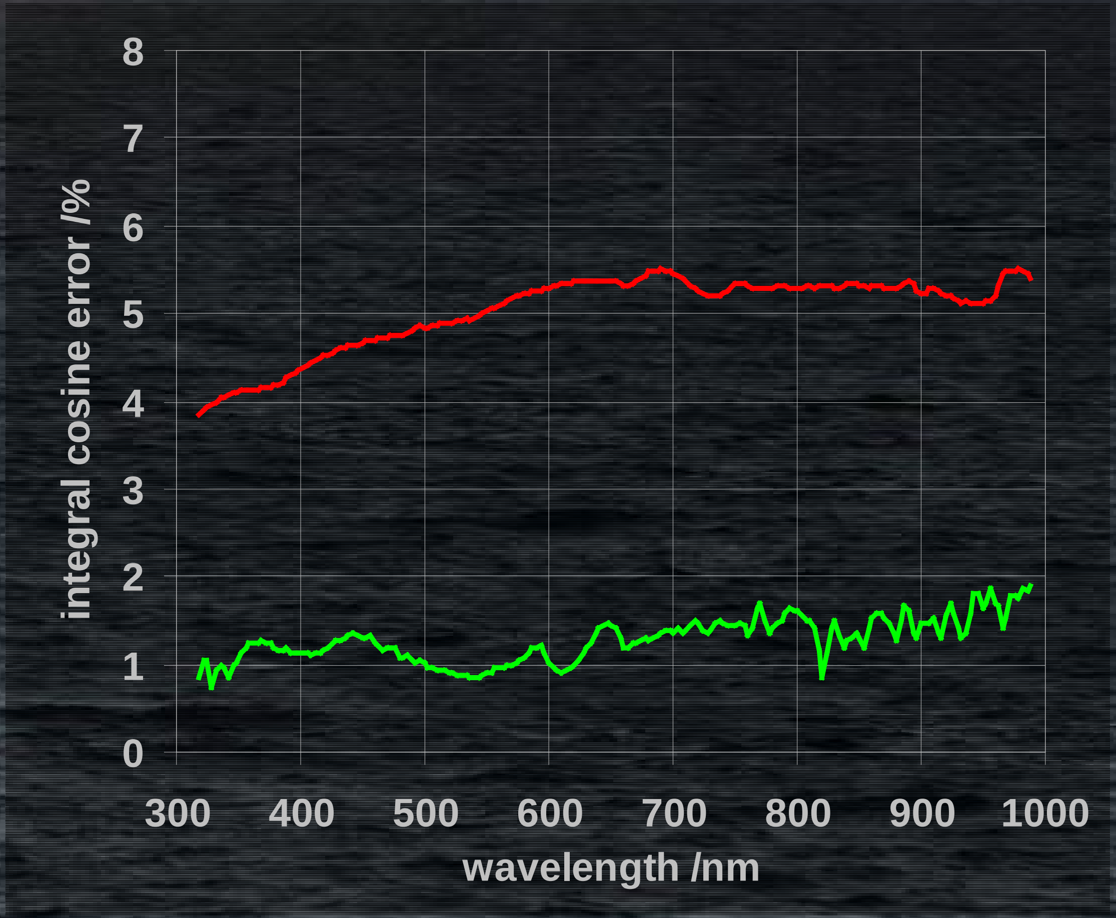
Reality: angular response deviates from the cosine law by "cosine error":

$$CE(\theta,\lambda) = \frac{S(\theta,\lambda)/S(\theta=0,\lambda) - \cos(\theta)}{\cos(\theta)} \cdot 100\%$$

The integral cosine error is defined as

$$ICE(\lambda) = \int_{0^\circ}^{85^\circ} CE(\theta,\lambda)\sin(2\theta)\,d\theta$$

Angular response examples



Reporting and uncertainty of the angular response

Cosine error for two principal planes (perpendicular to each other) with uncertainties are reported in the 'CP_*ANGULAR_*.txt' files.

Reproducibility (the alignment component) is the main uncertainty contributor. Evaluate with complete re-alignments.

The alignment can be easily tested by comparing the scans with azimuth angles 180° apart from each other.

Also the repeatability and the lamp stability contributions.

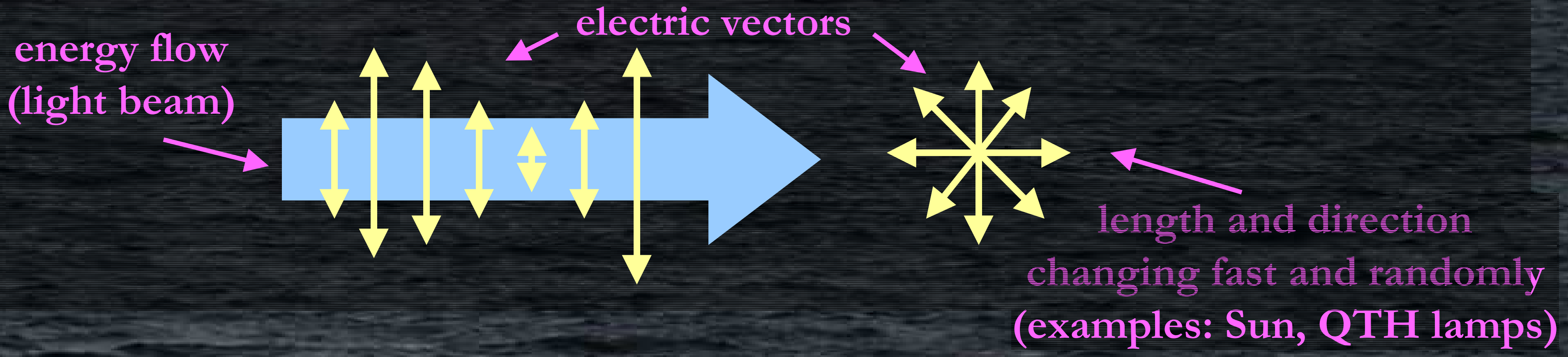
Polarization of light

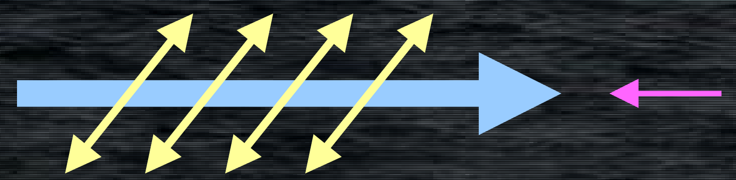
Optical radiation is an electromagnetic wave.

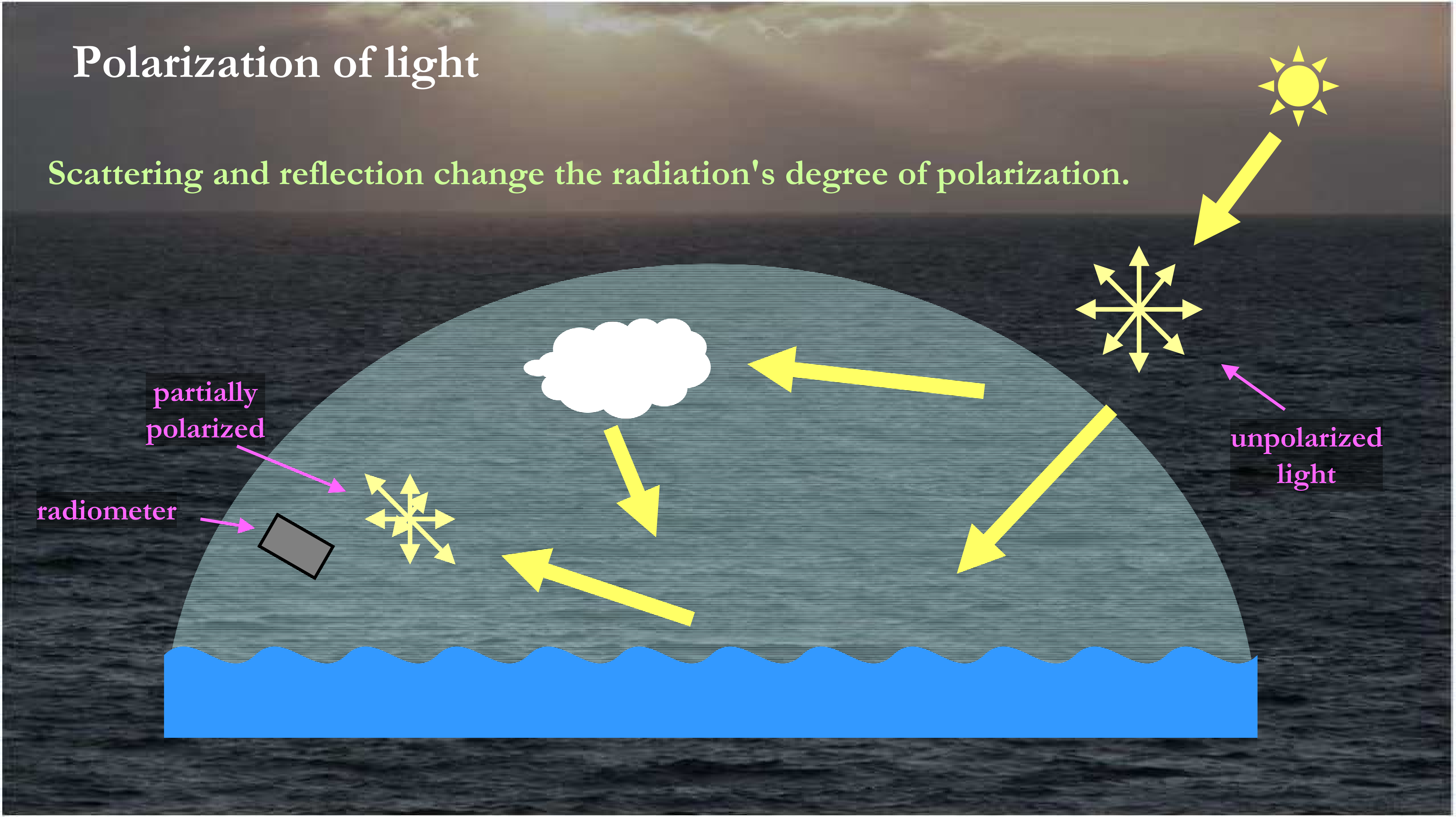
Electromagnetic waves are transverse: the electric and magnetic vectors are perpendicular to the direction of wave propagation.

In the case of unpolarized light, all vector directions have equal probability.

Light detectors <u>average</u> the electric vector magnitude into electrical signal.

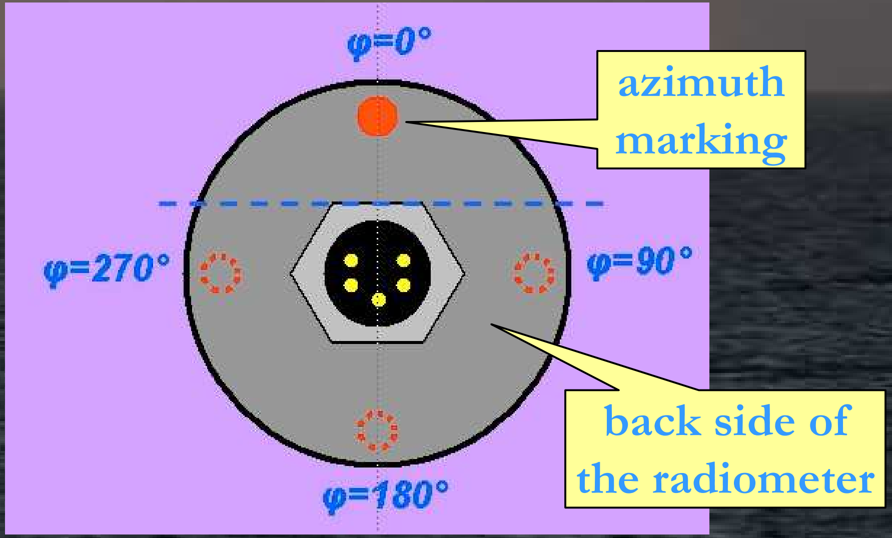


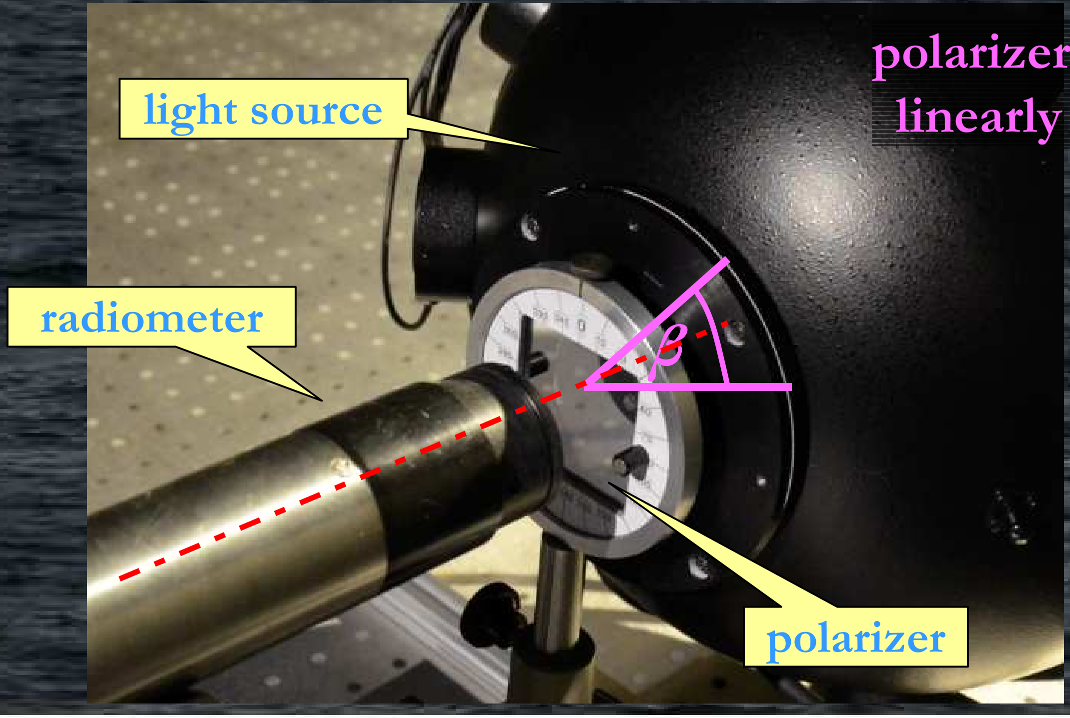



Polarization of light
Scattering and reflection change the radiation's degree of polarization.
partially polarized
radiometer
unpolarized light

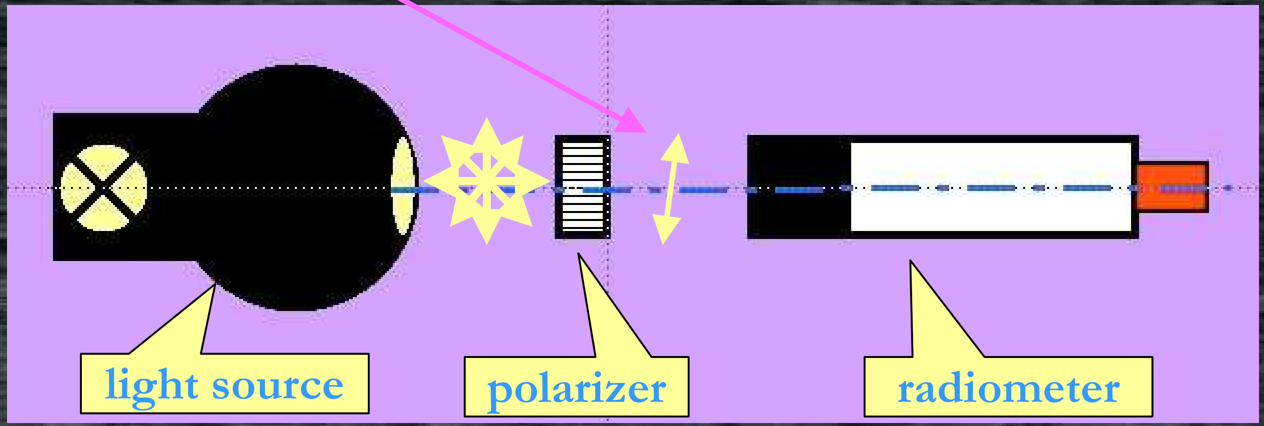
Measurement of the polarization sensitivity

Output radiation of the sphere is unpolarized.
Polaroid creates linearly polarized beam.
Polaroid is rotated around the optical axis and the radiometer's output signal recorded.
Angle of the maximum responsivity is referenced to the "red dot".





polarizer provides nearly linearly polarized light

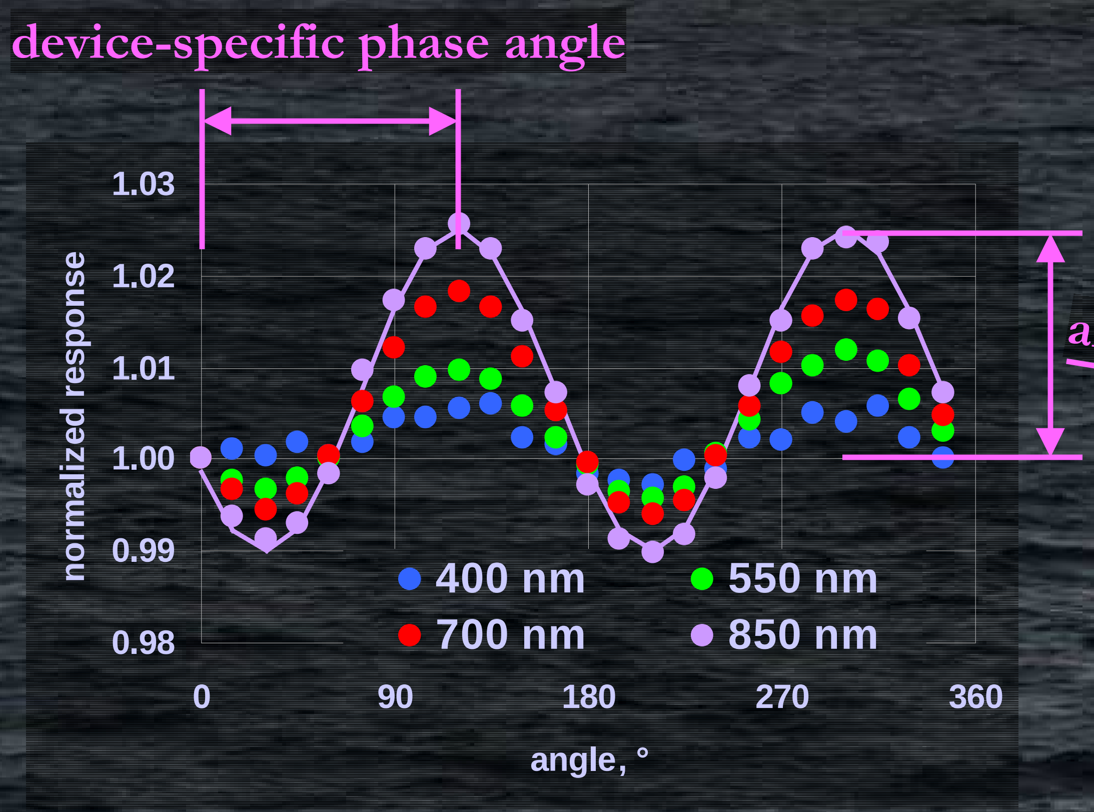


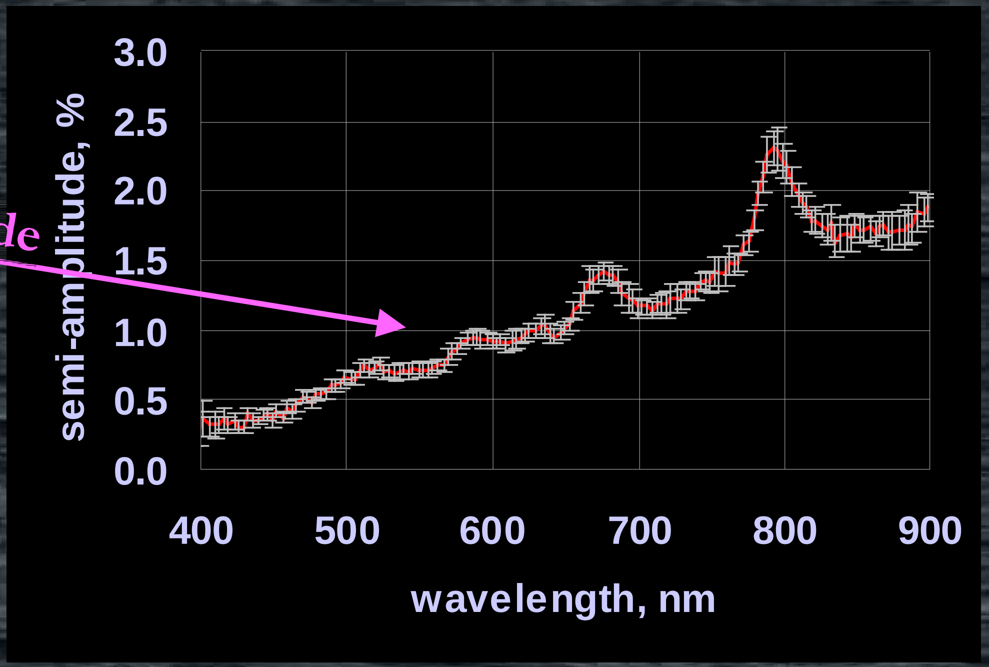
Measurement of the polarization sensitivity

Use unpolarized source (i.e. integrating sphere or reflectance panel)
and high quality wire grid polarizer.
The extinction ratio of the polarizer at single wavelength can be tested
with the HeNe laser and over the wavelength range with a Nicol prism.
Perform at least one full revolution of the polarizer to detect proper alignment.
Every now and then measure at initial polarizer angle to evaluate the source stability.
Refer to Talone 2016 & Kostkowski for the complete approach.

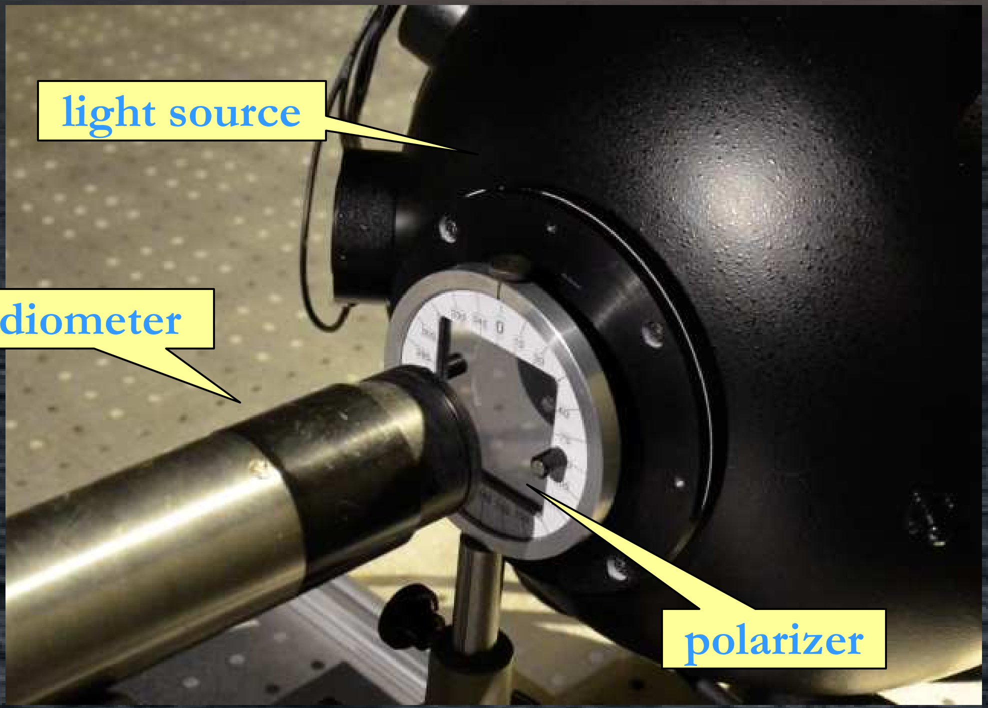
Polarization sensitivity example

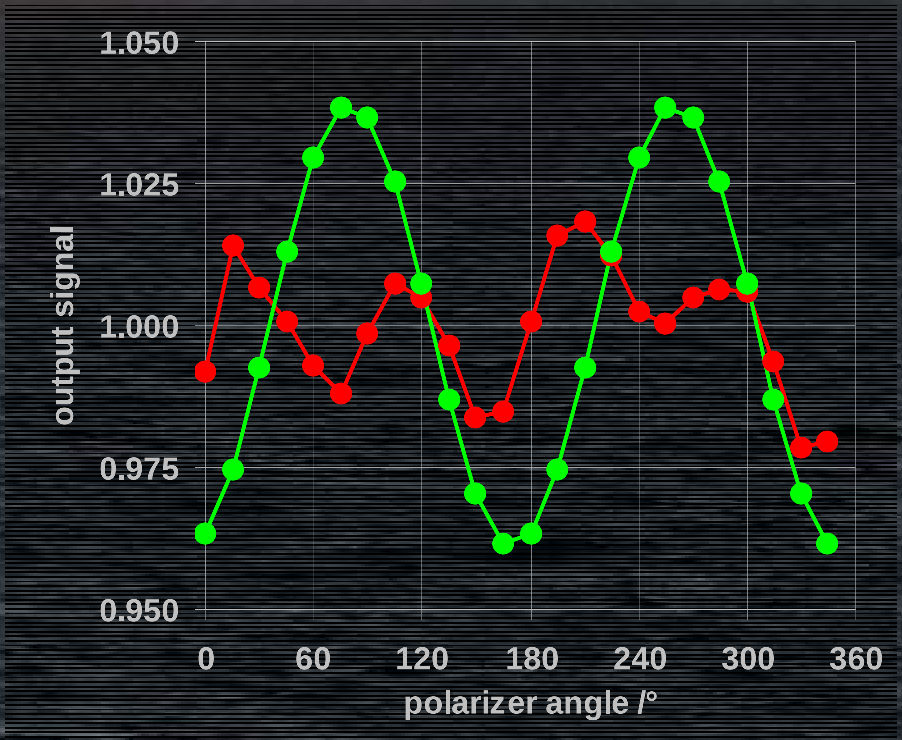
Because the detector acts on the magnitude of the electric vector, responsivity shows two maxima and minima per full rotation of the polarization plane.
Polarization sensitivity dependes on the wavelength.





Polarization sensitivity





Reporting and uncertainty of the polarization sensitivity

Amplitude and phase angle of the signal change are reported in the CP_*_POLAR_* files.

Perform the full re-alignment to assess the measurement reproducibility.

Rotate the radiometer by a known angle and repeat the measurements to assess the precision of the azimuth setting.

Include the uncertainty contributions from repeatability, source stability, and regression.

Other parameters, not implemented during FRM4SOC:

Temporal response

Ideal case: output signal of the radiometer corresponds to the temporal integral of the input flux during the integration time.

Reality: the output signal "remembers" previous flux or signal values.

Characterization method: test output signals at different integration times and illumination scenarios.

Remedy: drop a few spectra when changing the illumination level or integration time.

Other parameters, not implemented during FRM4SOC:

Accuracy of integration times

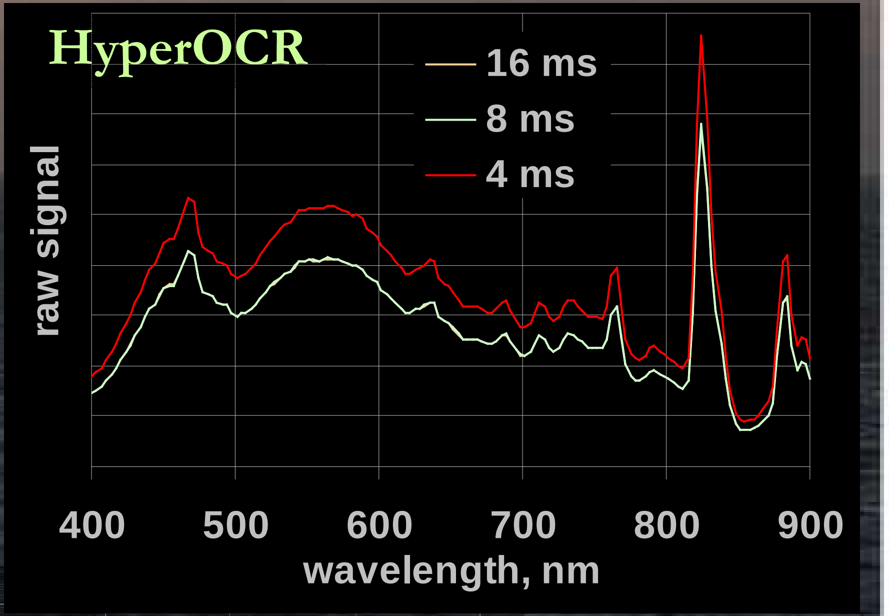
Characterization method: strobed light sources or reverse engineering.

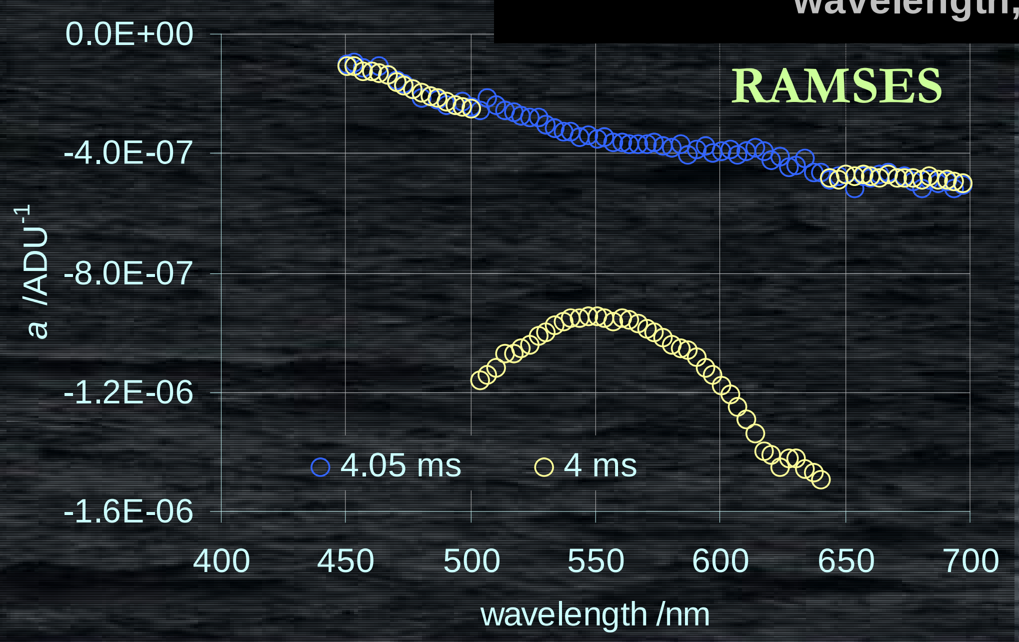
Discrepancies at the 4 ms integration time discovered during the non-linearity characterization of RAMSES and HyperOCR.

The shortest integration time for HyperOCR is actually 5 ms.

The shortest integration time for RAMSES is actually 4.05 ms.

Remedy: avoid the 4 ms integration time.





Other parameters, not implemented during FRM4SOC:

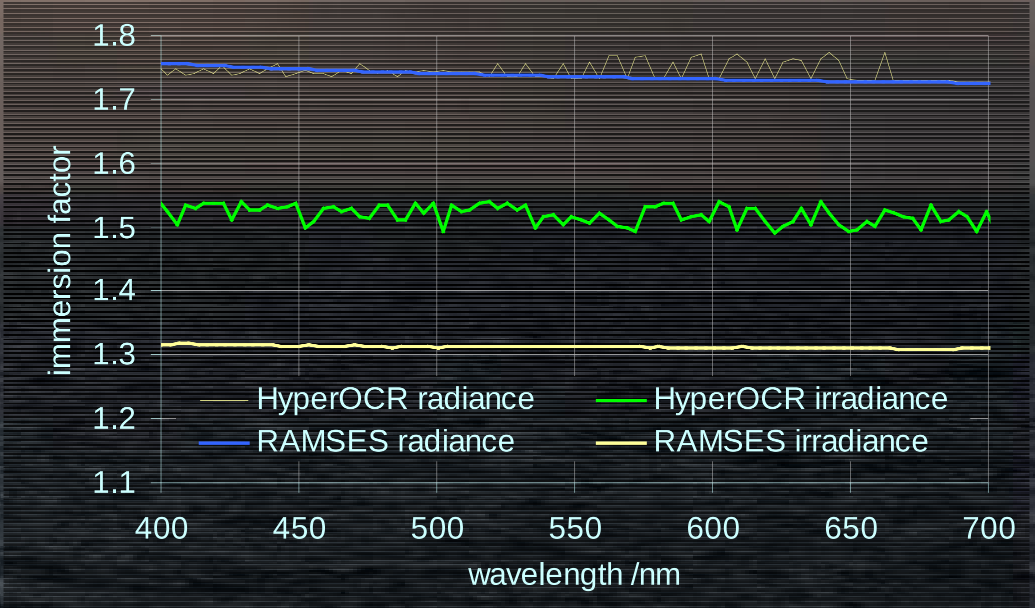
Immersion factors

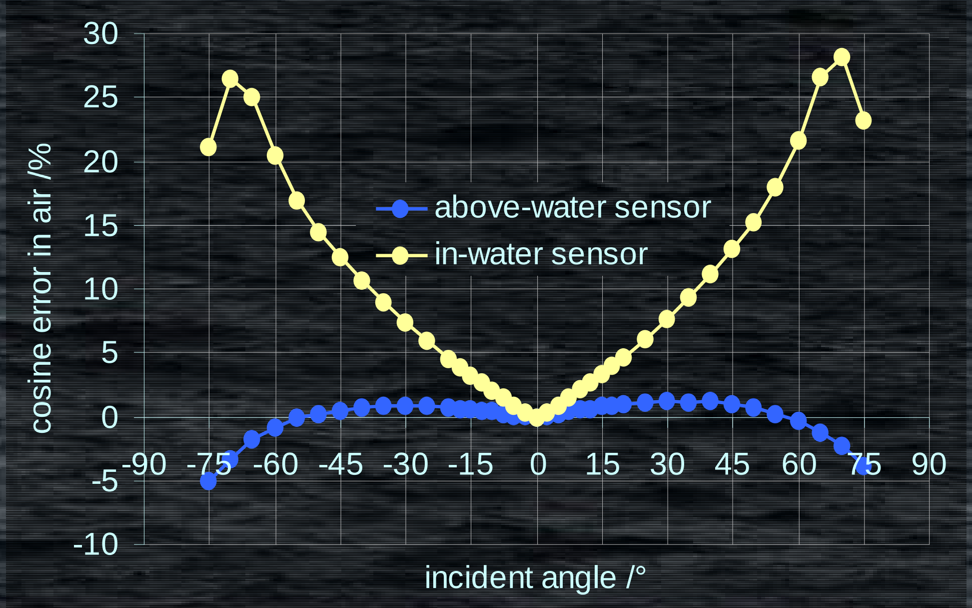
Radiometric responsivity depends on the refraction index of the environment (1 for air, 1.34 for seawater). Reasons: changes in the acceptance solid angles and in the boundary reflection & transmission.

Characterization method: direct determination by using spezialized water tank [Zibordi 2004].

Angular response depends on environment as well: HyperOCR is produced in two versions for in- and above-water applications while RAMSES is optimized for above-water.

Remedy: use proper calibration coefficients or apply immersion factors.





Other parameters, not implemented during FRM4SOC:

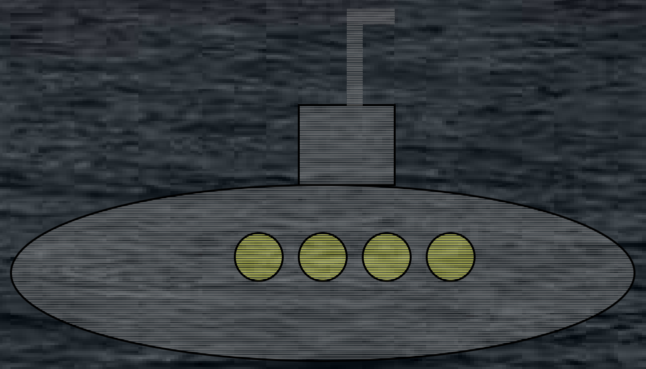
Pressure effects

Objectives: possible change of optical path inside the radiometer due to mechanical stress.

Proposed characterization method: barochamber with optical window.

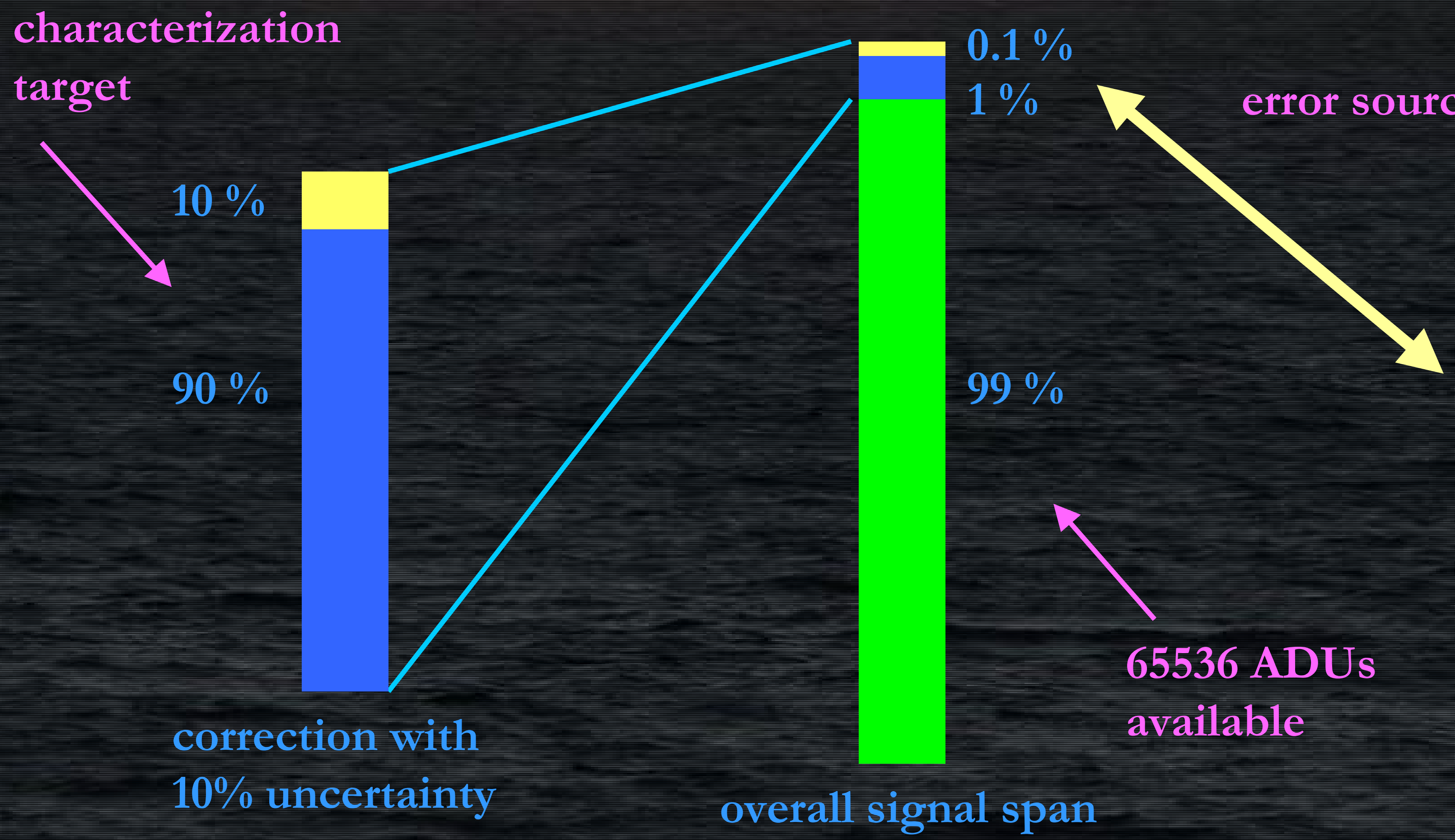
Not needed for above-water applications.

[Das Boot (1981)]



On the measurement precision

Unwanted drifts and SNR need to be suppressed to below 0.1 % level during the characterization measurements in order to achieve reasonable uncertainties.



error sources, % of the useful signal

non-linearity: 2 %

thermal: 2 % / 10°C

dark drift: 1.5% / °C

polarization: 1 %

source drift: 0.1 %

SNR: 0.1 %

In order to achieve the necessary precision:

Suppress unwanted thermal drifts by running the radiometers in expected way for at least 5 min before the actual measurements.
When possible, use short integration times.
Average as little as possible.
Keep measurement series sufficiently short and close to each other.
Measure the dark as often as possible.
Perform the reference measurement (when applicable) as often as possible.
Whenever possible, choose light source and intensity to equalize the raw signal.
Monitor the light sources and if necessary, correct for the monitor signal.
Keep the lab environment in tight limits. Avoid blowing the hot or cold air.

Suggestions to the manufacturers

Suppress unwanted thermal drifts by running the radiometers in expected way for at least 5 min before the actual measurements.
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Keep measurement series sufficiently short and close to each other.
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Summary

The instrument characterization is pretty much about experimenting as detailed instructions are rare.

Compare the results with other labs & references whenever possible.

The measurment facilities need throughout characterization, re-alignment and method adjustments in order to reveal the uncertainty sources.

When interested in characterization, start with the important ones: angular, non-linearity and thermal.