Radiometry, apparent optical properties: measurements and uncertainties

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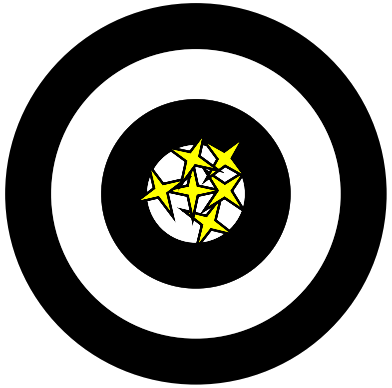
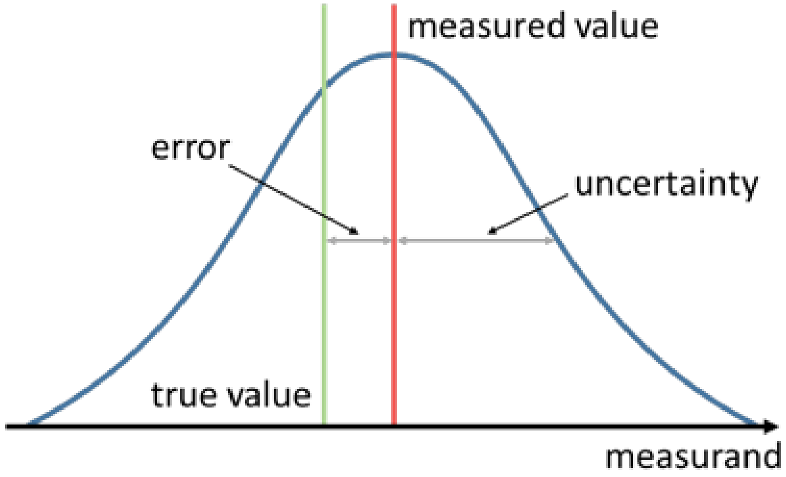
The quest for “truth”

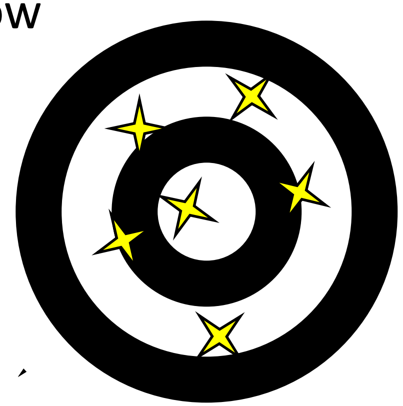
High precision,
Low accuracy,

High precision,
High accuracy,





High accuracy, Low precision, High uncertainty



Low accuracy,
Low precision,
High uncertainty

Why do we care about uncertainties?

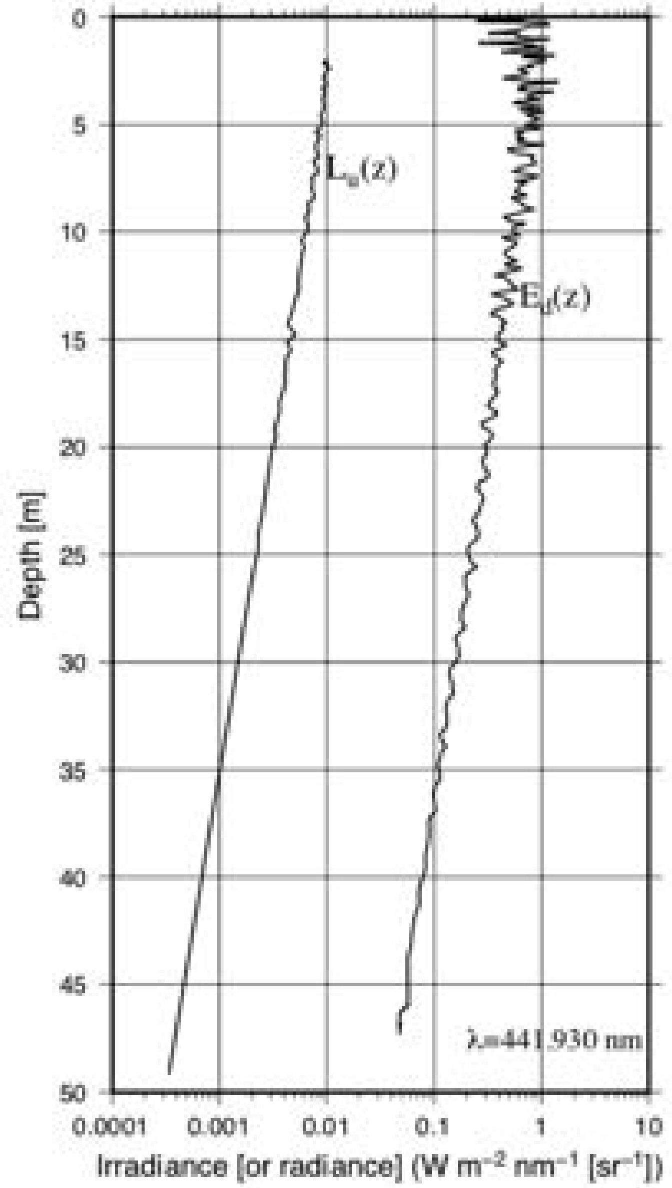
We want to:

- Do good science
- Be useful for space agencies by providing them with high-quality validation data
- Be useful for other potential users who have to make some decision from the data we provide
- Be able to quantify long-term trends in satellite ocean colour radiometry data (“climate-quality data records”)

That’s all about metrology and deployment protocols and data QC & processing techniques

The “Guide to the Expression of Uncertainty in Measurement” (GUM): https://www.bipm.org/documents/20126/2071204/JCGM_100_2008_E.pdf/cb0ef43f-baa5-11cf-3f85-4dcd86f77bd6

Let’s start simple



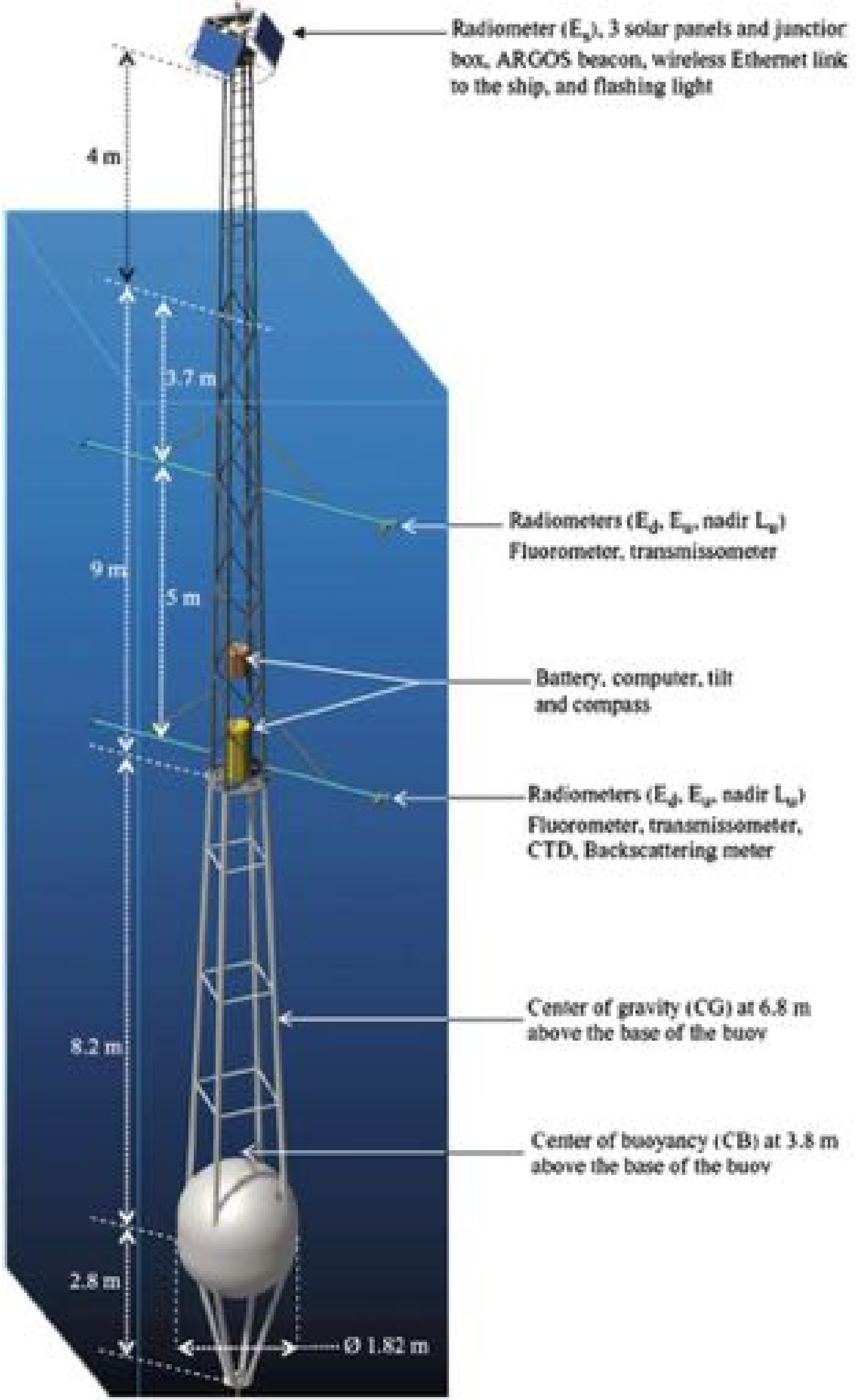
$$L_w = \frac{1 - \rho}{n^2} \underbrace{L_u(z)\, e^{K z}}_{L_u(0^-)}$$

With:

- ρ: water-air Fresnel reflection coefficient
- n: refractive index of seawater
- $L_u(z)$: upwelling radiance at depth z
- K: diffuse attenuation coefficient for L_u

Is it actually that “simple”?

Where the uncertainties come from?

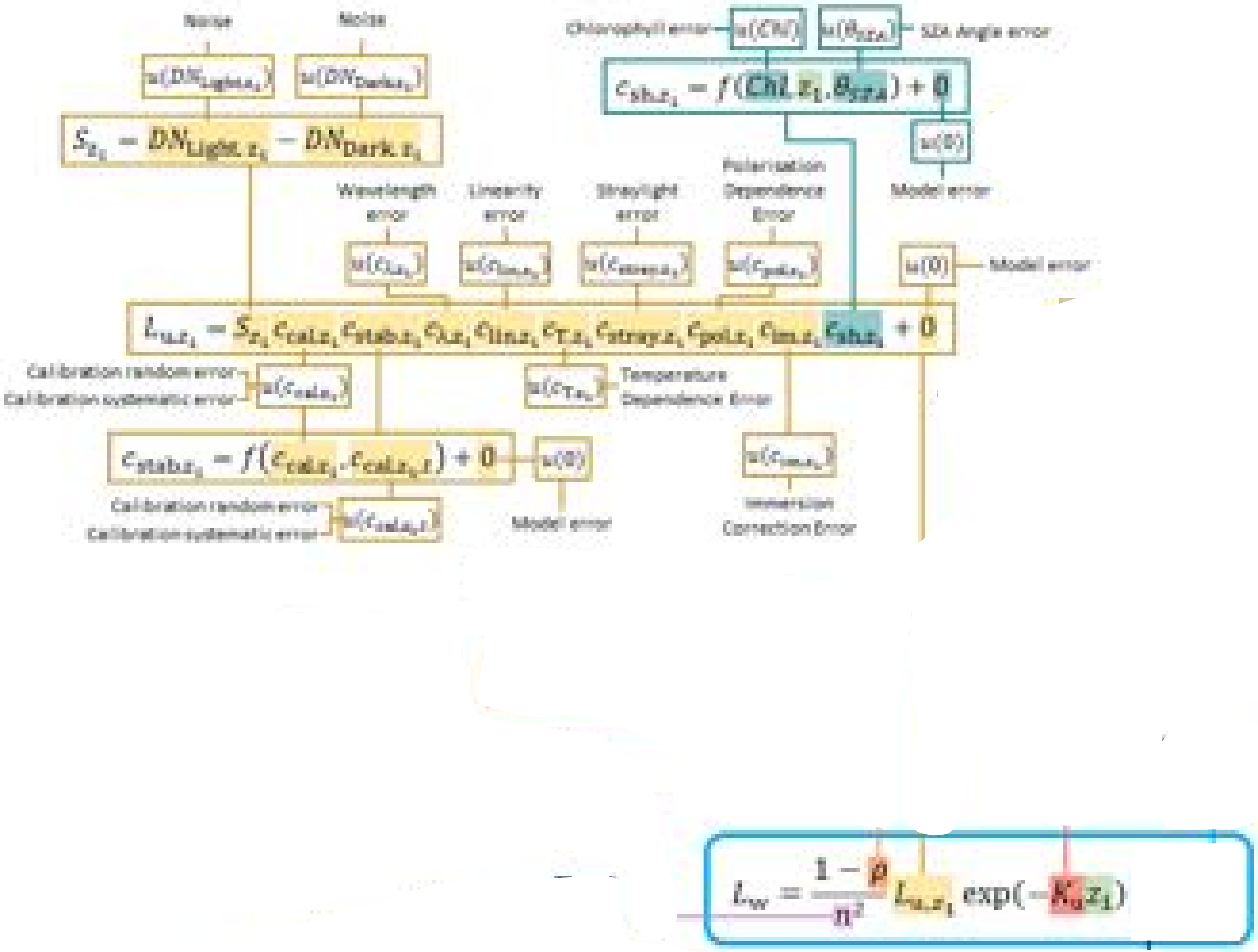


A practical example: the BOUSSOLE buoy

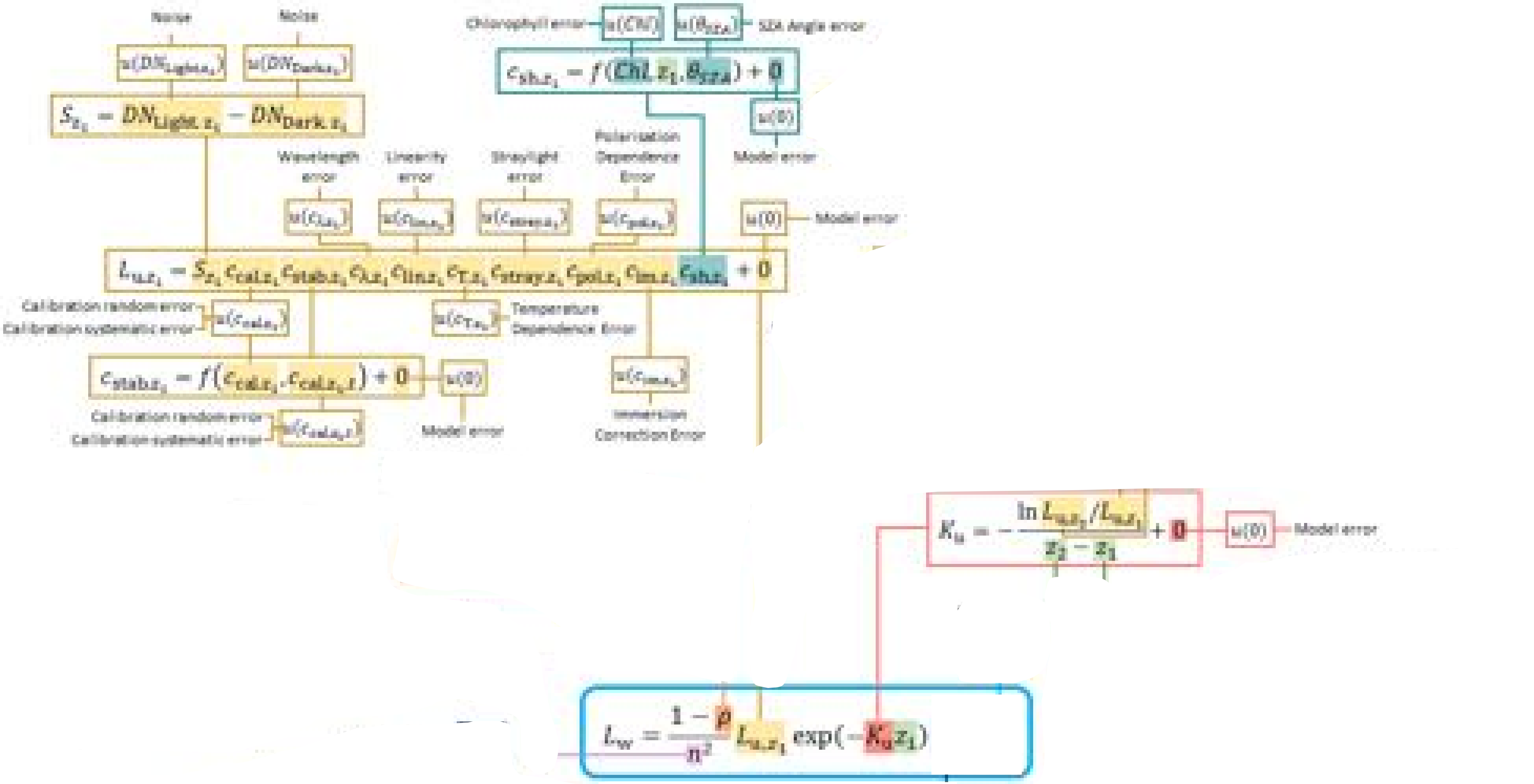
- $L_u(z)$, $E_u(z)$ and $E_d(z)$ measured at 2 depths
- E_s measured at +4.5 m above sea level
- Used to derive R_{rs}

$$K_{Lu} = \ln\left(\frac{L_u(z_1)}{L_u(z_2)}\right)/(z_2 - z_1)$$

$$L_w = \frac{1-\rho}{n^2} L_{u,z_1} \exp(-K_u z_1)$$



Noise
Noise
Chlorophyll error
SZA Angle error
Model error
Wavelength error
Linearity error
Straylight error
Polarisation Dependence Error
Model error
Calibration random error
Calibration systematic error
Temperature Dependence Error
Calibration random error
Calibration systematic error
Model error
Immersion Correction Error



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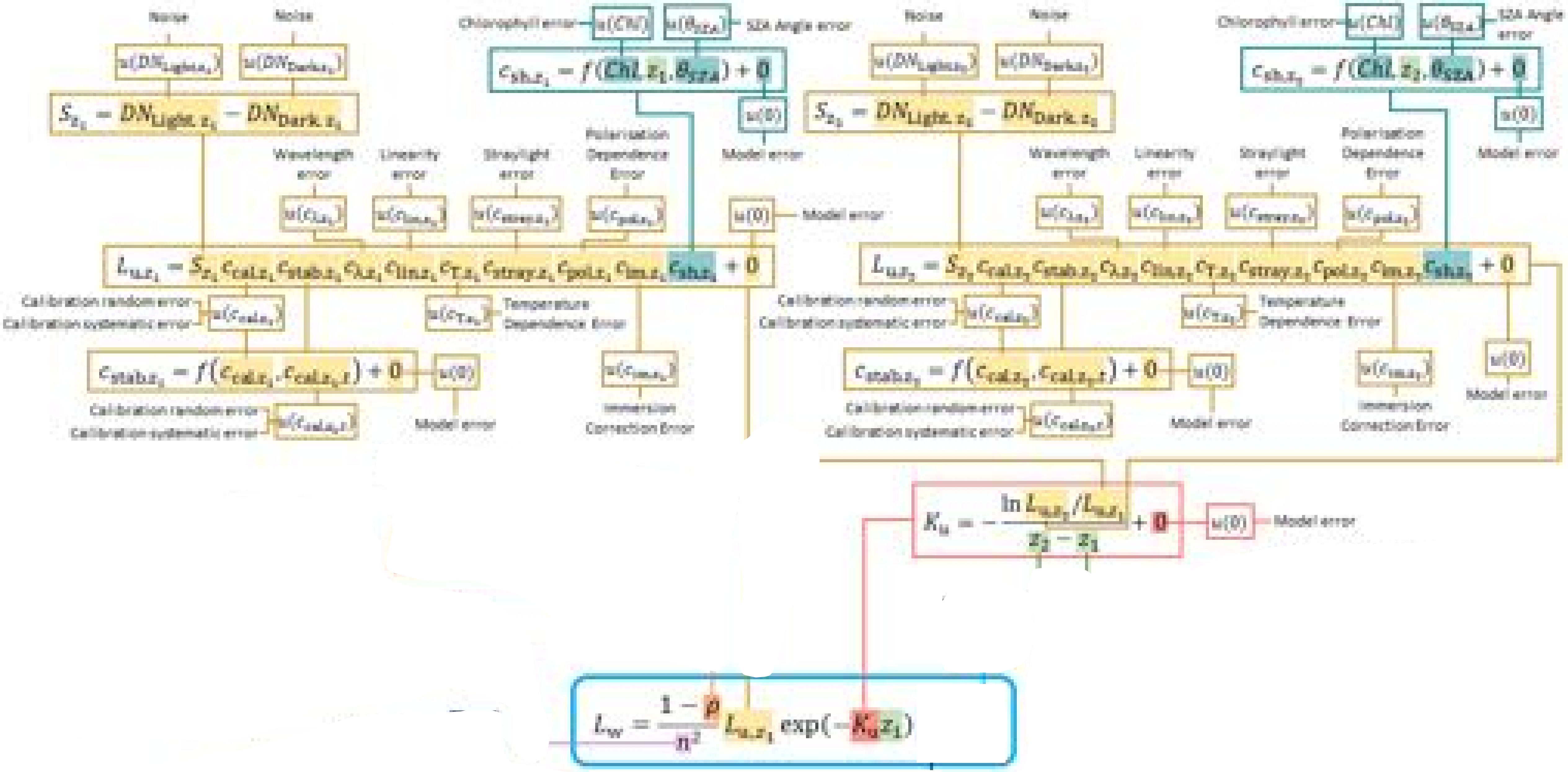

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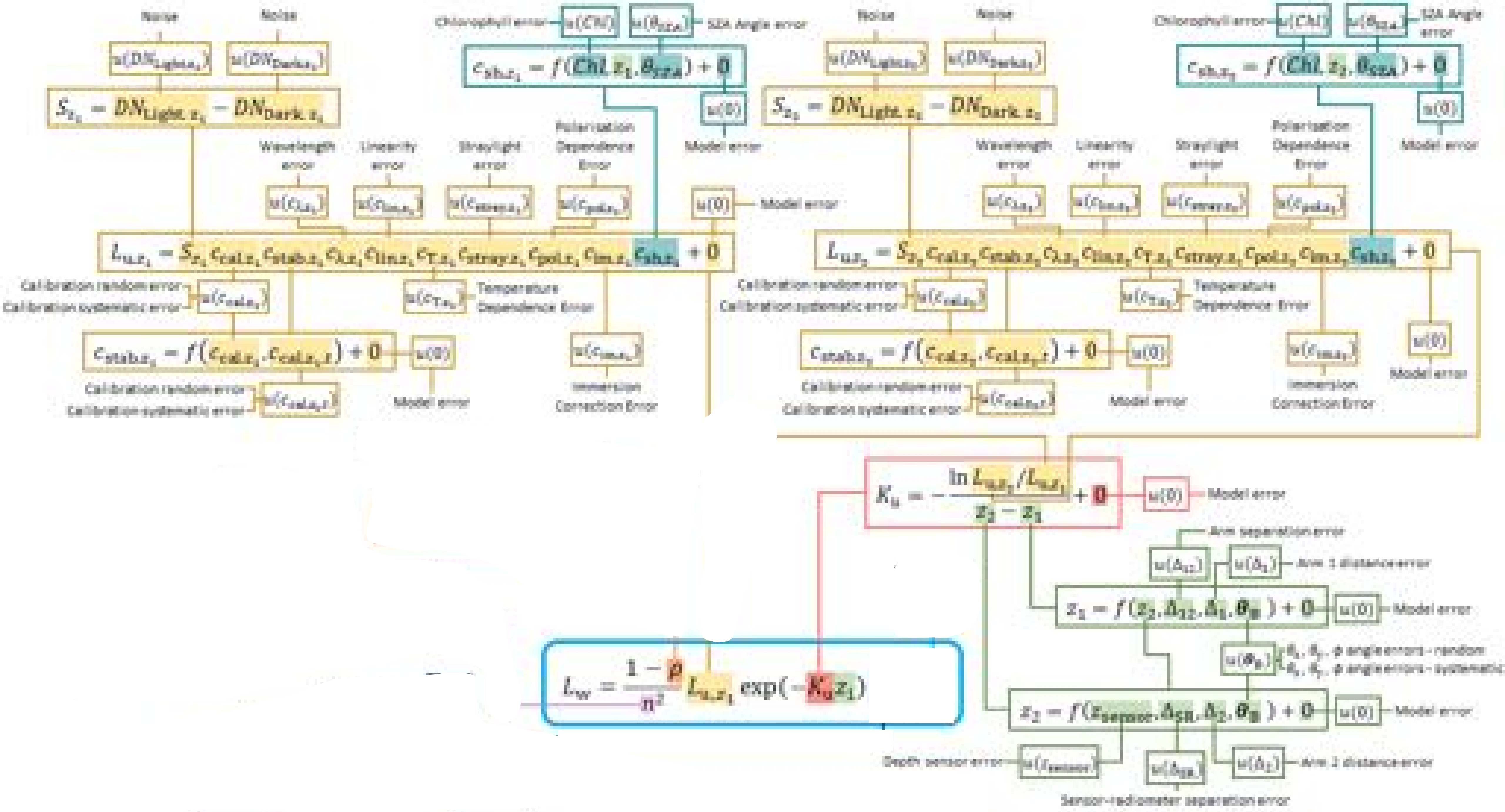

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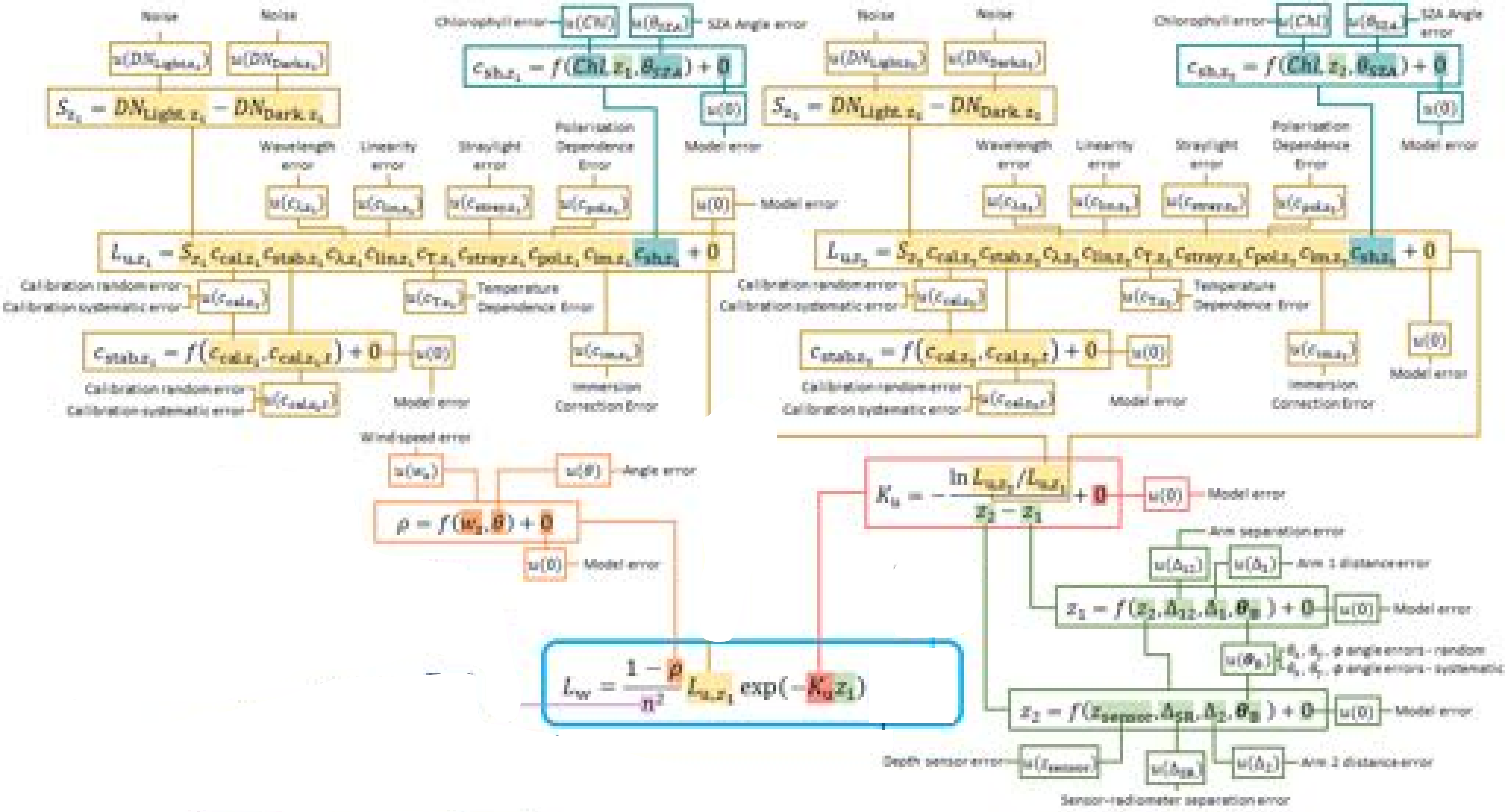
Arm separation error
Arm 1 distance error
Depth sensor error
Arm 2 distance error
Sensor-radiometer separation error



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Straylight error
Polarisation Dependence Error
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Wind speed error
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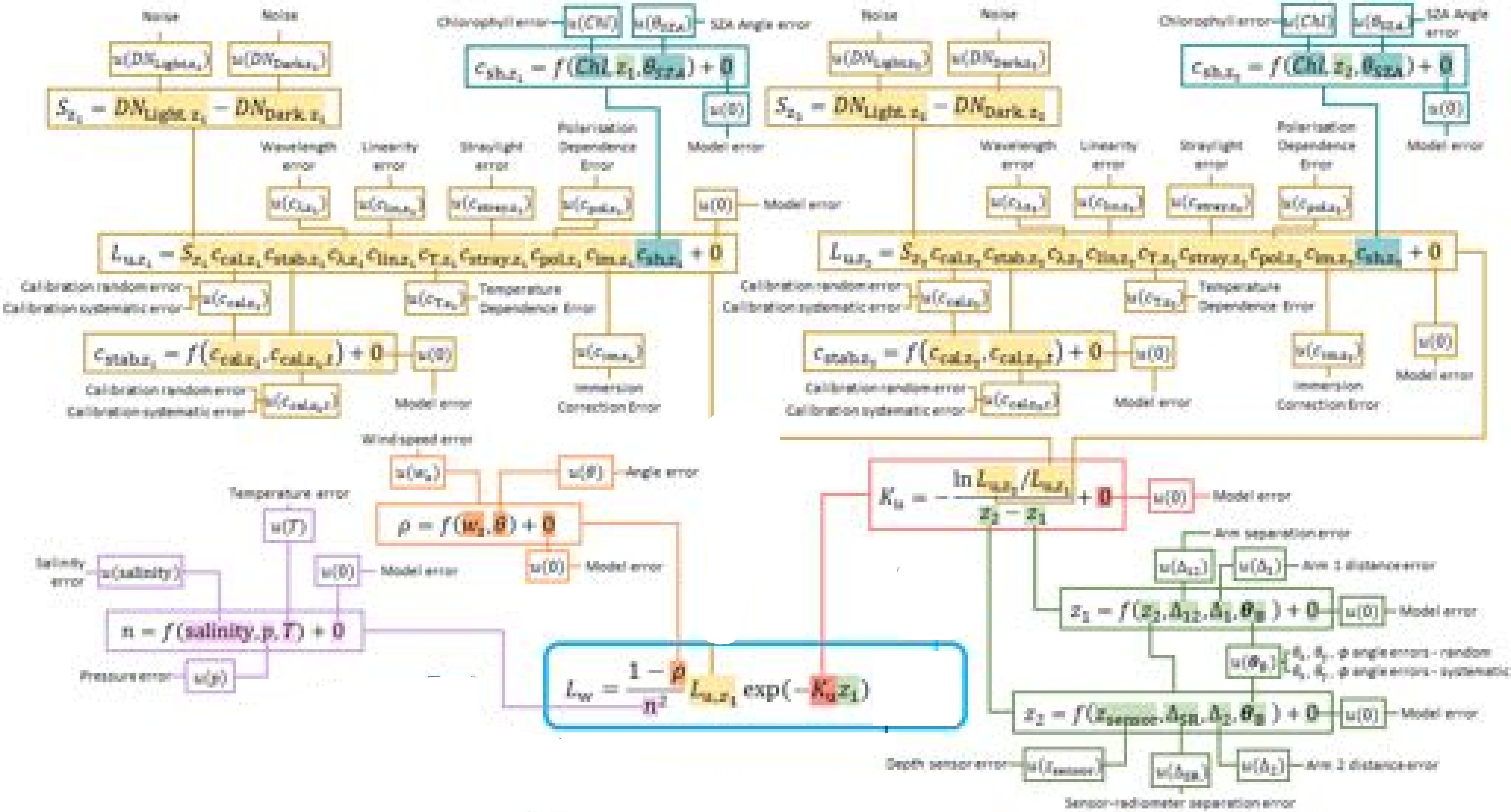
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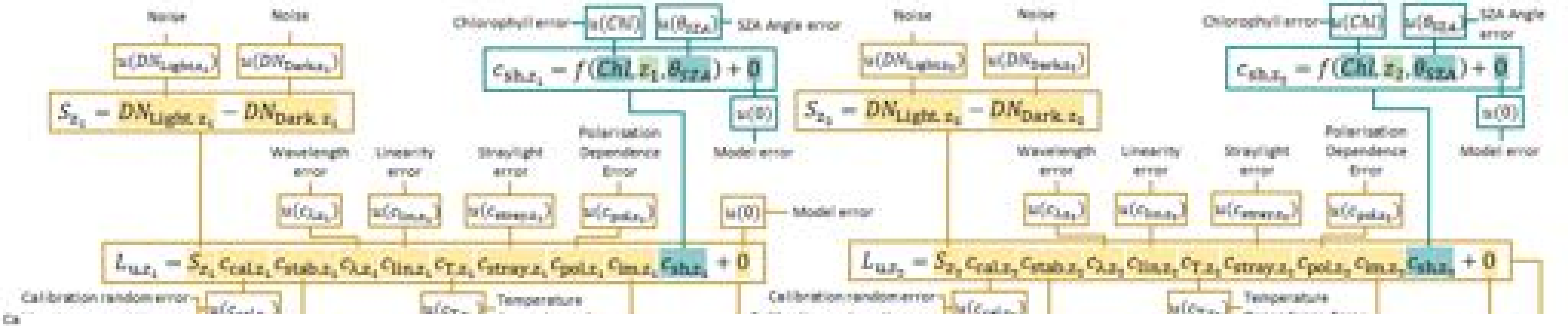
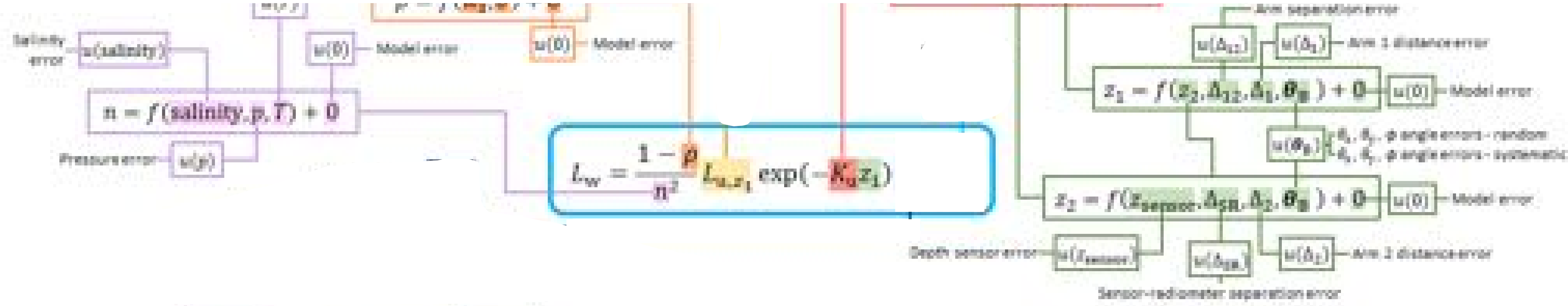


Bialek, A., V. Vellucci, B. Gentili, D. Antoine, J. Gorroño, N. Fox and C. Underwood, 2020. Monte Carlo–Based Quantification of Uncertainties in Determining Ocean Remote Sensing Reflectance from Underwater Fixed-Depth Radiometry Measurements, J. Atmos. Ocean. Tech. 37, DOI: 10.1175/JTECH-D-19-0049.1



Combining uncertainties

If $x,\ldots,w$ are measured with independent and random uncertainties $\delta x,\ldots,\delta w$, and are used to compute $q = x + \ldots + z - (u + \ldots + w)$, then the uncertainty in q is the quadratic sum:

$$\delta q = \sqrt{(\delta x)^2 + \ldots + (\delta z)^2 + (\delta u)^2 + \ldots + (\delta w)^2}$$

If $x,\ldots,z$ are measured with independent and random uncertainties $\delta x,\ldots,\delta z$ and are used to compute $q(x,\ldots,z)$ then the uncertainty in q is

$$\delta q = \sqrt{\left(\frac{\partial q}{\partial x}\delta x\right)^2 + \ldots + \left(\frac{\partial q}{\partial z}\delta z\right)^2}$$

From R. Palmer, "Propagation of Uncertainty through Mathematical Operations"
https://web.mit.edu/fluids-modules/www/exper_techniques/2.Propagation_of_Uncertaint.pdf

What do we do if uncertainties are not independent and random?

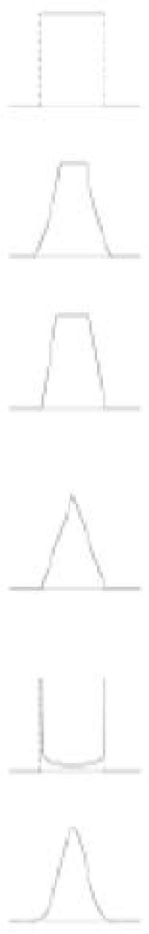
- **One option is the "Monte Carlo" technique**:

1- Define the "Probability distribution functions" of individual uncertainties (can be normal, log normal, rectangular, …) and the sensitivity coefficients

2- Run the measurement equation multiple times, each time with a different subset of values for each of the uncertainty sources. These values are randomly "picked" from the PDFs, hence the "Monte Carlo" terminology

3- Produce enough outputs so that you end up with a distribution of the quantity of interest, e.g., L_w.

4- The average and stdev of this distribution will give you the uncertainty



Type A and B uncertainties

- Type A uncertainty:

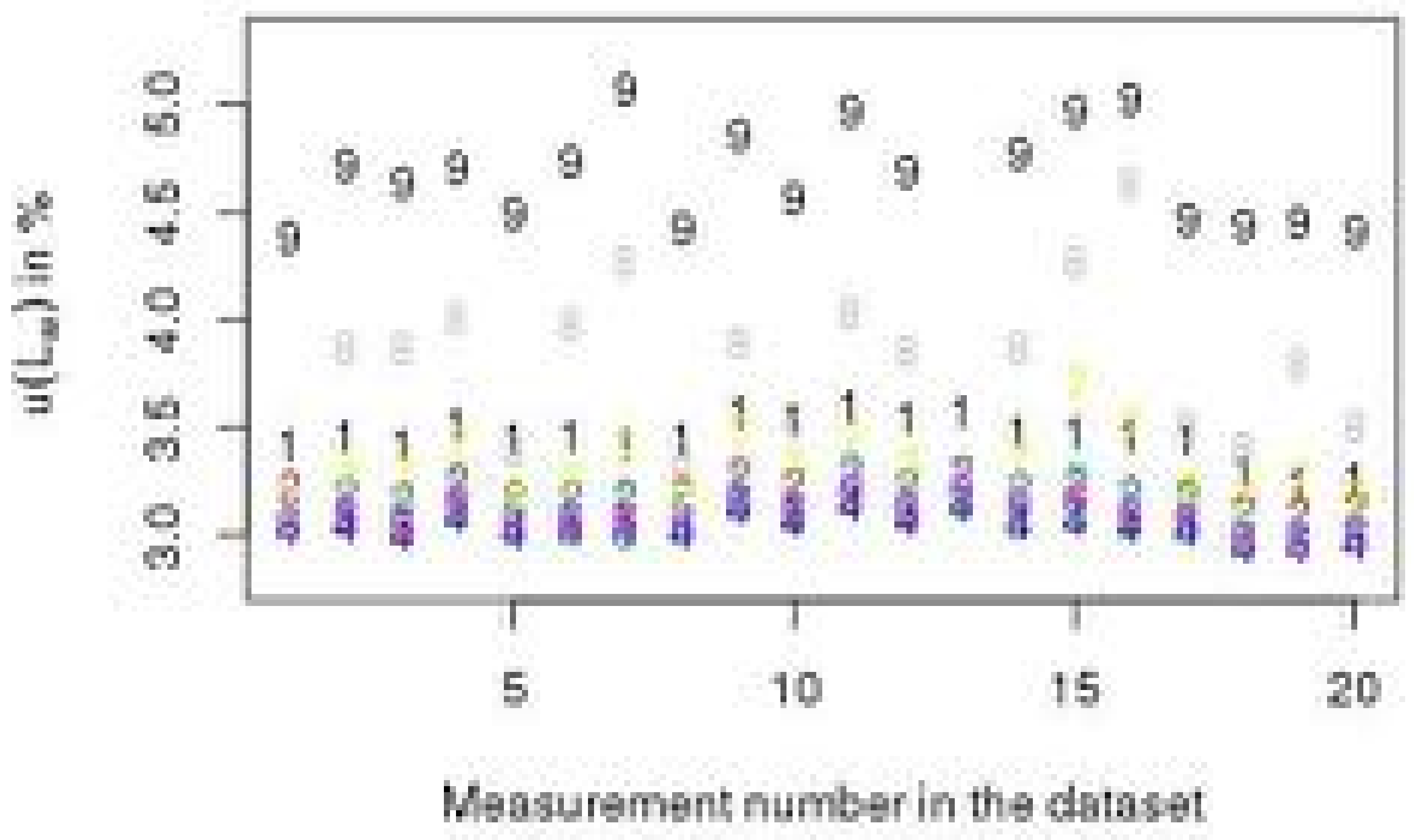
- You can derive it from a series of measurements.
- This is essentially the variance of the mean

- Type B uncertainty (from the "GUM")

When the standard uncertainty is evaluated by scientific judgement based on all of the available information on the possible variability. The pool of information may include:

- previous measurement data;
- experience with or general knowledge of the behaviour and properties of relevant materials and instruments;
- manufacturer's specifications;
- data provided in calibration and other certificates;
- uncertainties assigned to reference data taken from handbooks.

Example at BOUSSOLE



Relative uncertainty in L_w

Antoine D, Vellucci V, Banks AC, Bardey P, Bretagnon M, Bruniquel V, Deru A, Hembise Fanton d'Andon O, Lerebourg C, Mangin A, Crozel D, Victori S, Kalampokis A, Karageorgis AP, Petihakis G, Psarra S, Golbol M, Leymarie E, Bialek A, Fox N, Hunt S, Kuusk J, Laizans K, Kanakidou M. ROSACE: A Proposed European Design for the Copernicus Ocean Colour System Vicarious Calibration Infrastructure. Remote Sensing. 2020; 12(10):1535. https://doi.org/10.3390/rs12101535

Confidence intervals

- Uncertainty is given with respect to a given confidence interval:

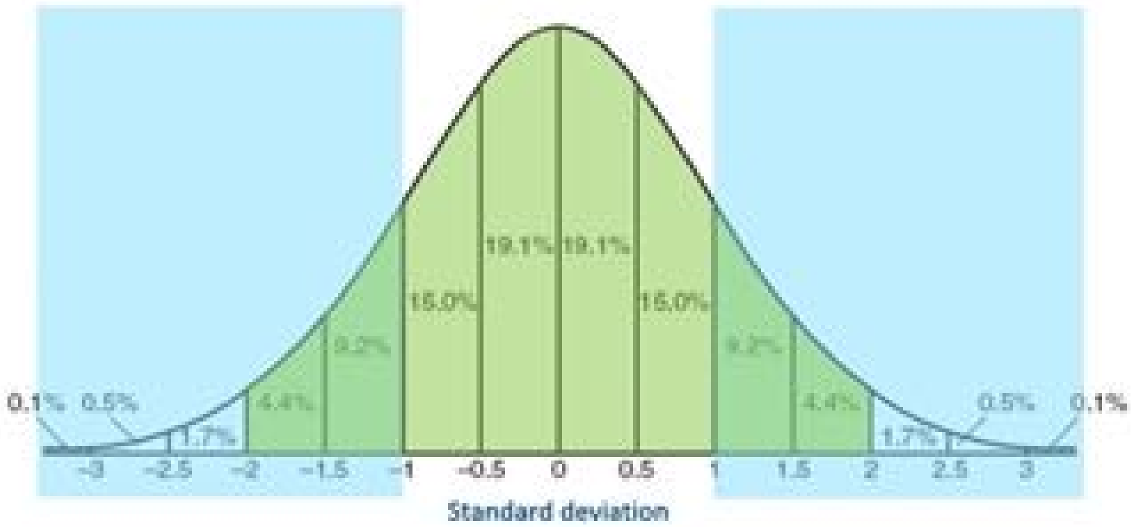
$u(y) = \pm 3$ cm

at the 68.2% coverage probability (1σ or $k = 1$)

at the 95.4% confidence level

$u(y) = \pm 6$ cm

at the 95.4% coverage probability (2σ or $k = 2$)



Slide from A. Bialek, 2016

More on uncertainties

Lectures by Agnieska Bialek, IOCCG SLS 2016

https://www.ioccg.org/training/SLS-2016/Bialek-L1.pdf

https://youtu.be/V4bCOCnu3cQ

https://www.ioccg.org/training/SLS-2016/Bialek-L2.pdf

https://youtu.be/rYyzVCId7FI

The "Guide to the Expression of Uncertainty in Measurement" (GUM):
https://www.bipm.org/documents/20126/2071204/JCGM_100_2008_E.pdf/cb0ef43f-baa5-11cf-3f85-4dcd86f77bd6

Uncertainty sources

- Instrument itself

- How it is deployed in the field

- How quantities of interest (e.g., R_{rs}) are derived from the measurements

Instrument-related uncertainty sources

Radiant Flux and its conversion

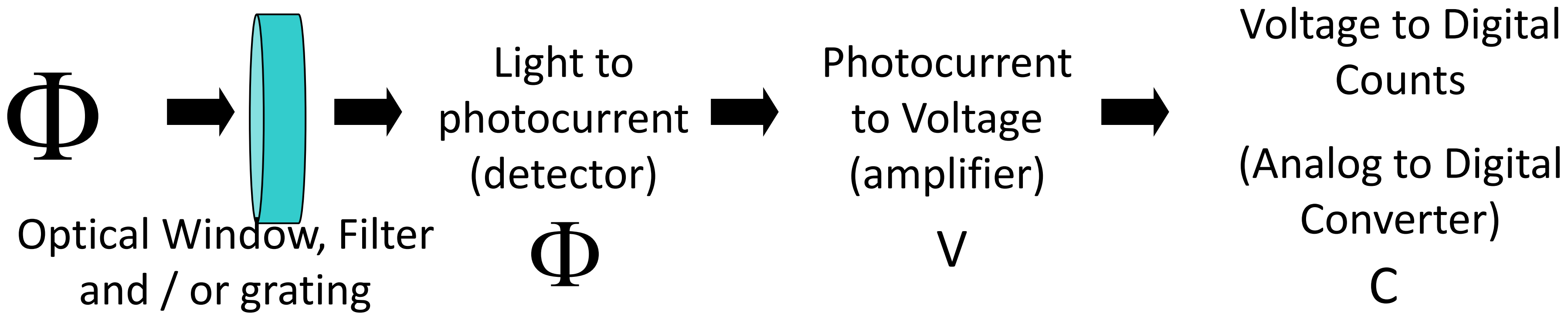
Quantity	Symbol	SI units	Abbreviation	Notes
Radiant Energy	*Q*	joule	J	energy
Radiant Flux	*Φ*	watt	W	radiant energy per unit time, so called radiant power
Radiance	*L*	watts per square metre per steradian	W/m^2/sr	power per unit solid angle per unit projected source area
Irradiance	*E*	watts per square metre	W/m^2	power incident on a surface

Radiant Flux (Power)

joules (energy) / time

$$\Phi = \frac{dQ}{dt}$$

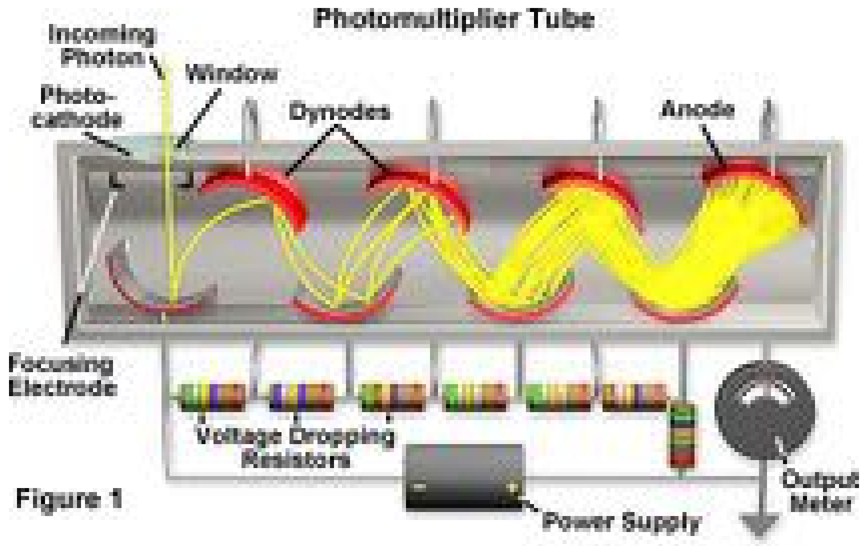
Measured by Quantum (photon) Detectors



Light Detectors

Photomultiplier tube (PMT)

- photoelectric effect - electron dislodged from the metal cathode amplified by successive dynodes to produce electron 'cascade'
- extremely sensitive light detectors
- degradation of dynodes due to electron bombardment
- stable, high voltages needed (power consumption)
- thermal effects



http://learn.hamamatsu.com/articles/photomultipliers.html

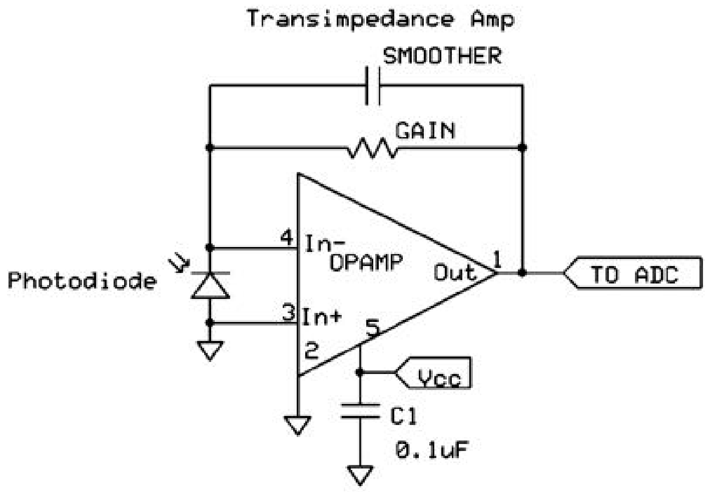
Semiconductors (i.e., silicon photodiodes used in PAR sensors, OCRs etc.)

- photon-induced excitation of electrons to the conduction band of the silicon, producing a current

Diode Arrays (like HOCR, DALEC, Ramses)

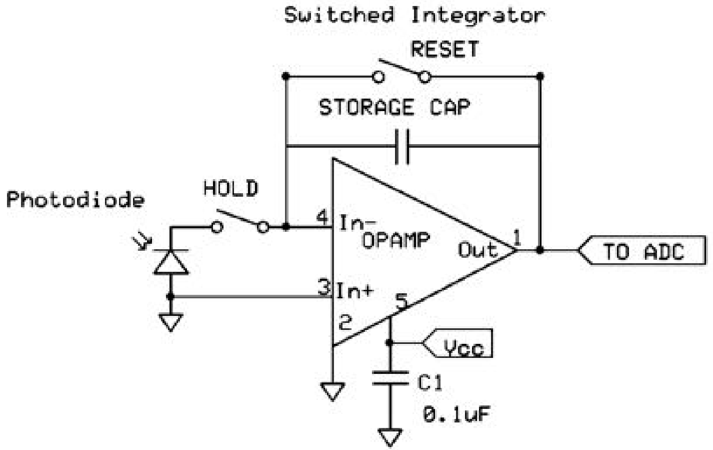
- Linear or 2D area arrays of small photodiode 'pixels' i.e., 256 pixels @ ~10um spacing
- Allows direct alignment with a diffracted beam (spectral resolution) or imaging (2D)
- Pixels usually need to be 'read out' sequentially – lower sampling rate

Current to Voltage Converters



Transimpedance Amp

- Sensitivity defined by **gain resistor**
- Instantaneous voltage output, directly proportional to photocurrent
- Feedback capacitor acts as temporal "smoother" filter
- Common approach used in individual photodiode-based sensors i.e. PAR and multispectral where signal is strong

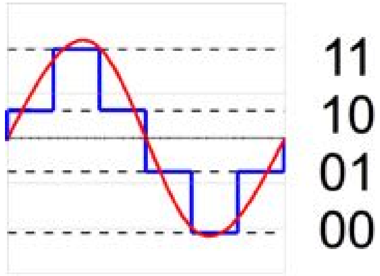


Switched Integrator Amp

- Sensitivity defined by storage **capacitance value** AND the **duration** that the Reset switch is open
- Time - discrete voltage 'readouts'
- This is where spectrometer "Integration Time" comes from
- Used for diffraction-based devices where signal is low (diode array spectrometers)

Analog (V) to Digital Conversion

Converts analog (continuous) voltage data into discretised “counts”



There are many different (~15) types of ADC architecture.

ADC Resolution defined as the number of digital numbers used to represent the converted analog photo current

- 2-bit resolution = 2^2 = 4 Counts (as shown above)
- 10-bit resolution = 2^{10} = 1024 Counts
- 16-bit resolution = 2^{16} = 65536 Counts

ADC resolution does not necessarily equate to measurement resolution, might be digitizing noise.

https://commons.wikimedia.org/wiki/File:2-bit_resolution_analog_comparison.png

What to do about this?

- Instrument design adapted to what type of measurements are aimed at and in which environment

- Instrument laboratory characterization

- Instrument laboratory calibration

Instrument design

- Size, shape (self shading, ease of use)
- Heat dissipation (in-water or in-air instrument)
- Collectors design (in-water or in-air instrument)
- Design and quality of the optics
- Quality of the detectors (linearity, dynamic range, SNR, blooming?)
- Choice of electronics
- Internal temperature control
- Internal temperature measurement

Instrument lab characterisation

A number of instrument characteristics have to be assessed (quantified)

- Linearity of the detectors' response
- Spectral calibration
- Spectral band response functions (filters)
- Immersion coefficients
- Temperature dependence
- Sensitivity to polarization of the incoming (ir)radiance
- Straylight
- ....

Instrument lab calibration

Radiometric Calibration

- Need to compare the sensor's digital counts to a radiant flux standard so we can quantify light accurately.
- See Ocean Optics Protocols

Ocean Optics Protocols For Satellite Ocean Color Sensor Validation, Revision 4, Volume II:

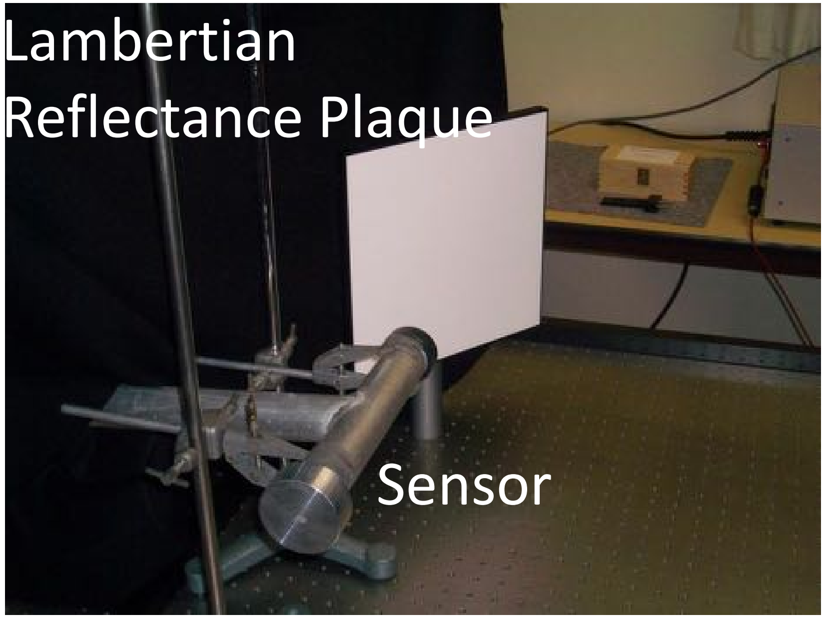
Instrument Specifications, Characterization and Calibration

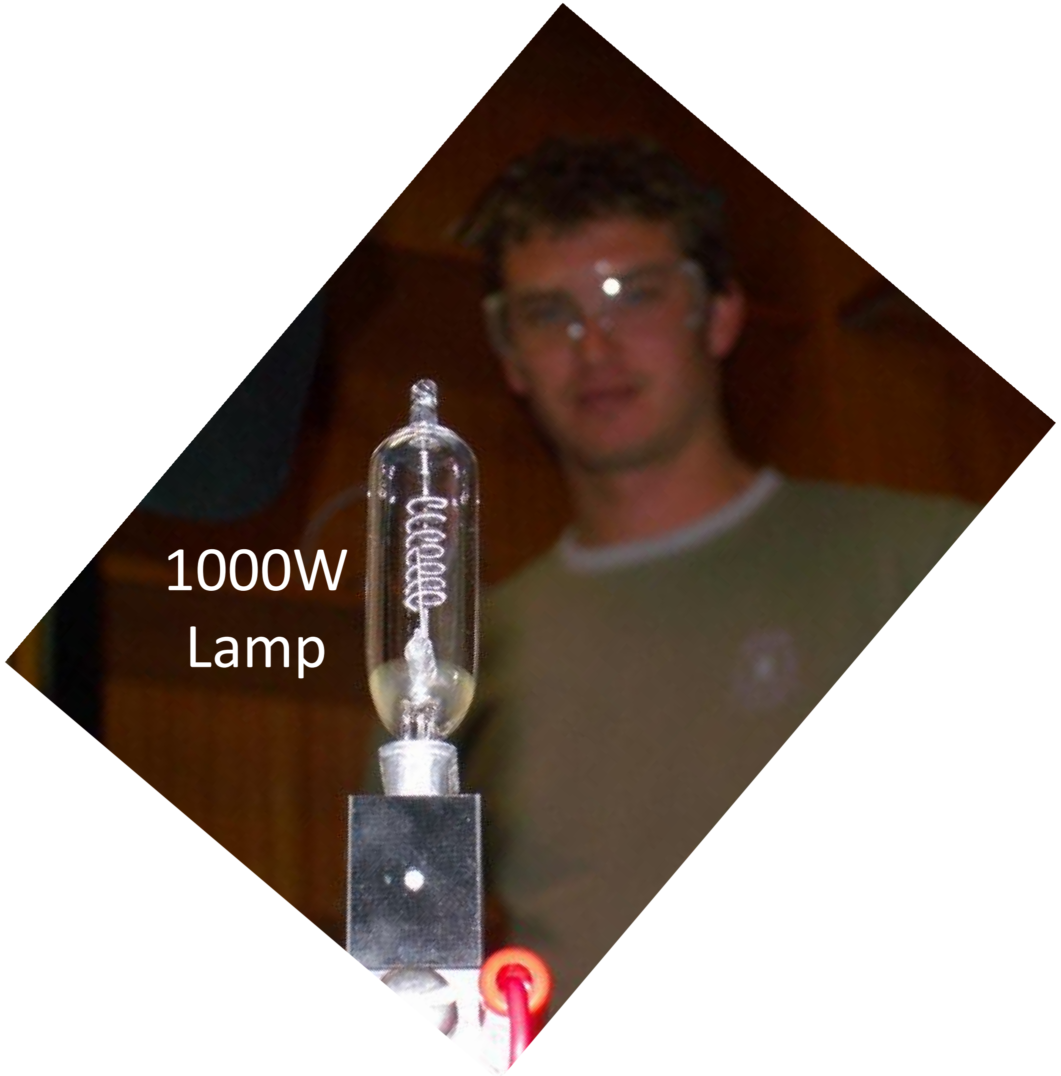
NASA/TM-2003-21621/Rev-Vol II

James L. Mueller, Giulietta S. Fargion and Charles R. McClain, Editors
J. L. Mueller, C. Pietras, S. B. Hooker, R.W. Austin, M. Miller, K.D. Knobelspiesse, R. Frouin, B. Holben and K. Voss, Authors.

Radiometric Calibration

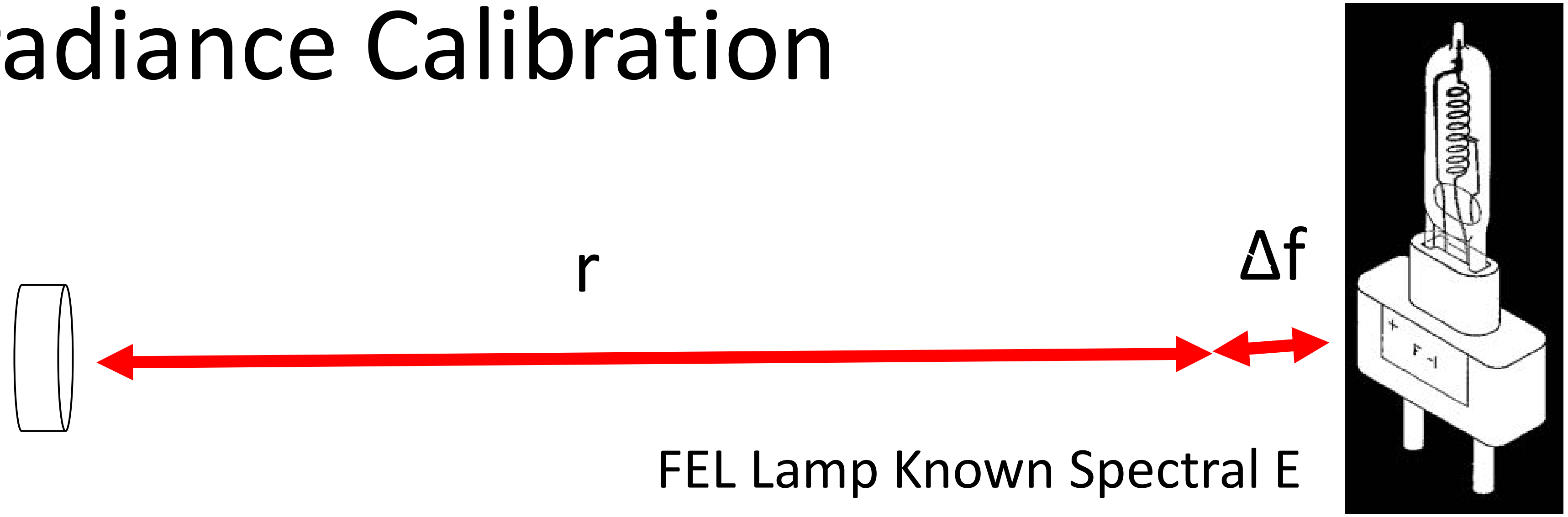
- Need (at minimum)
  - a stable calibrated power supply
  - a NIST-traceable FEL lamp
  - Lambertian reflector for L (NIST)





Irradiance Calibration

E / Cosine Collector

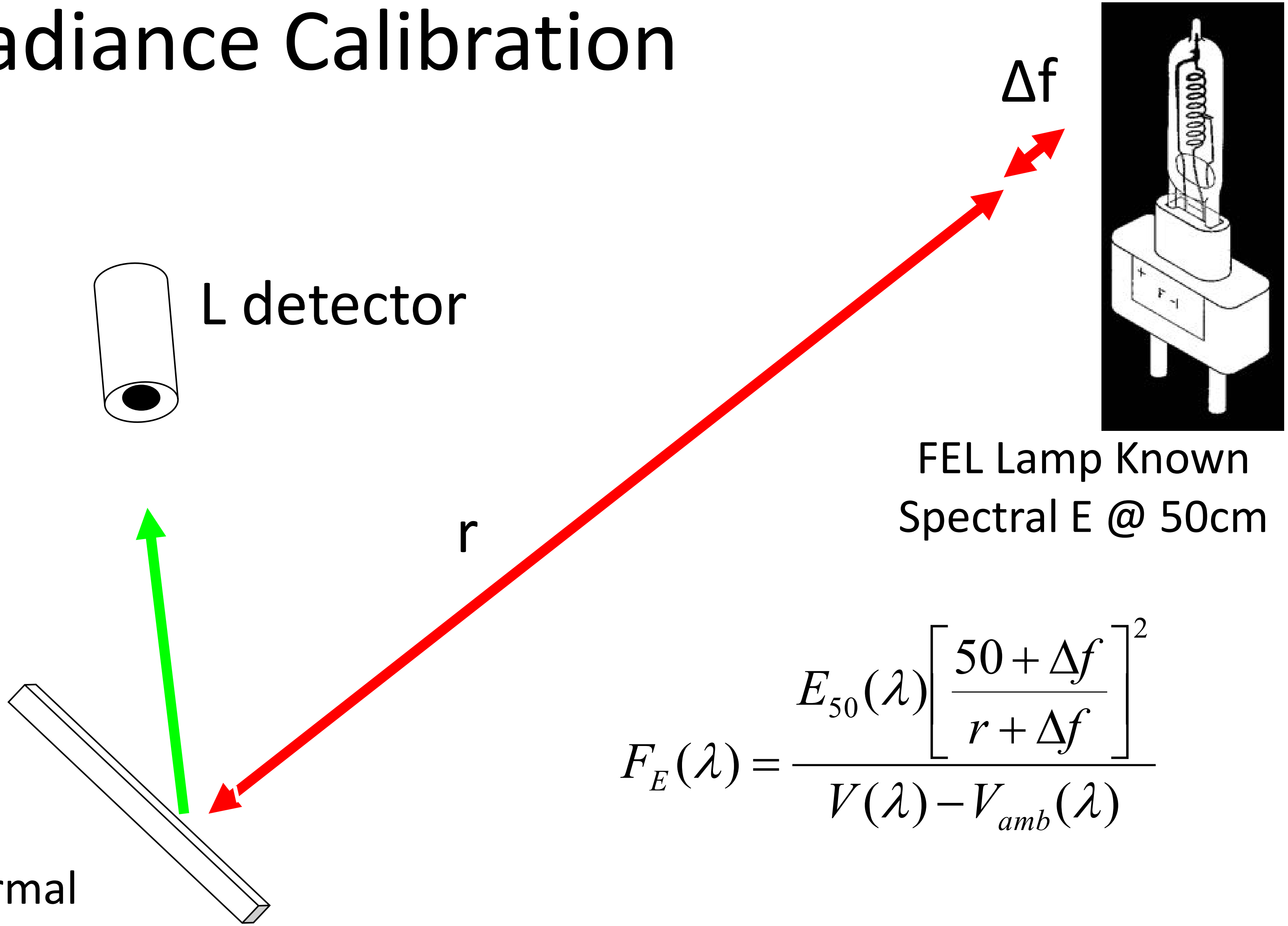


FEL Lamp Known Spectral E @ 50cm

$$F_E(\lambda) = \frac{E_{50}(\lambda)\left[\frac{50+\Delta f}{r+\Delta f}\right]^2}{V(\lambda) - V_{amb}(\lambda)}$$

$$E(\lambda) = F_E(\lambda)[V(\lambda) - V_{dark}]\mu W cm^{-2} nm^{-1}$$

Radiance Calibration



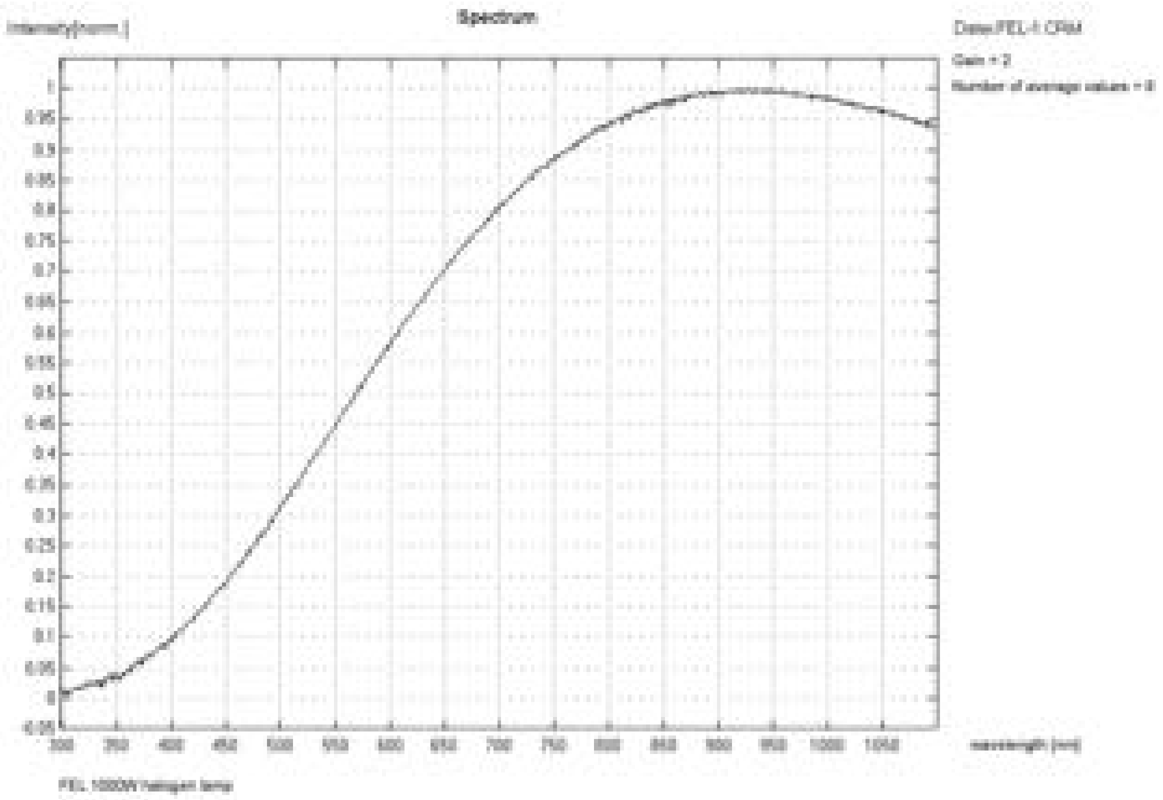
$$F_E(\lambda) = \frac{E_{50}(\lambda)\left[\dfrac{50+\Delta f}{r+\Delta f}\right]^2}{V(\lambda) - V_{amb}(\lambda)}$$

$$L(\lambda) = \frac{1}{\pi}\boxed{\rho(\lambda, 0^{\circ}, 45^{\circ})} F_E(\lambda)[V(\lambda) - V_{dark}]\mu W cm^{-2} sr^{-1} nm^{-1}$$

Calibration Uncertainty

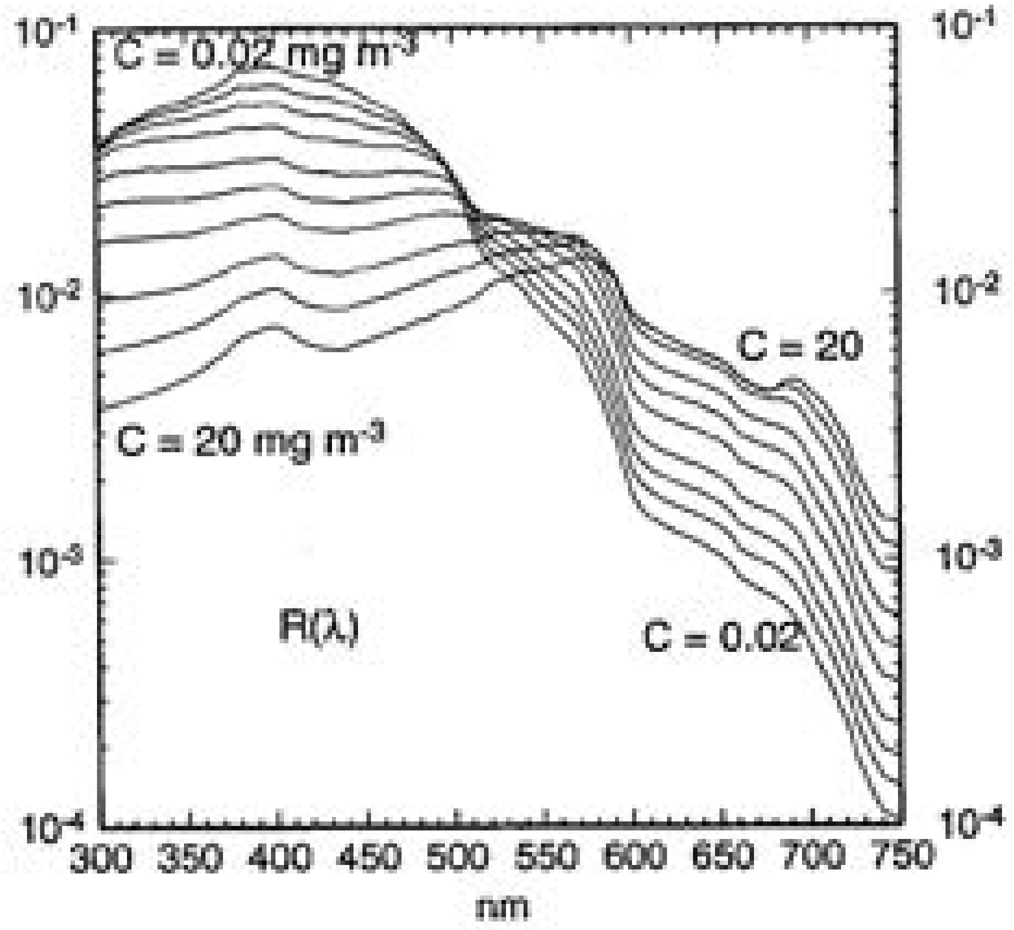
- Lamp calibration coefficients E_{50} are within 1% of NIST when less than 1 year old, and less than 50 hours burn time…
- Scale E_{50} using distance "r" between plaque and lamp surface.
  - Measure it accurately without touching the lamp or the lambertian reflector? +/- 1mm hopefully
- Δ-f. (distance between the filament and lamp surface) Which part of the filament?
- Spectralon Plaque Reflectivity / Cleanliness
- Power supply accuracy is important (8A)
  - Buy a good (expensive) one
  - Verify voltage over calibrated shunt resistors V=IR
- Relies on the wavelength calibration of detector
  - use line emission source to verify and compensate if necessary, they do drift! i.e. 4nm in 15 years

Calibration source



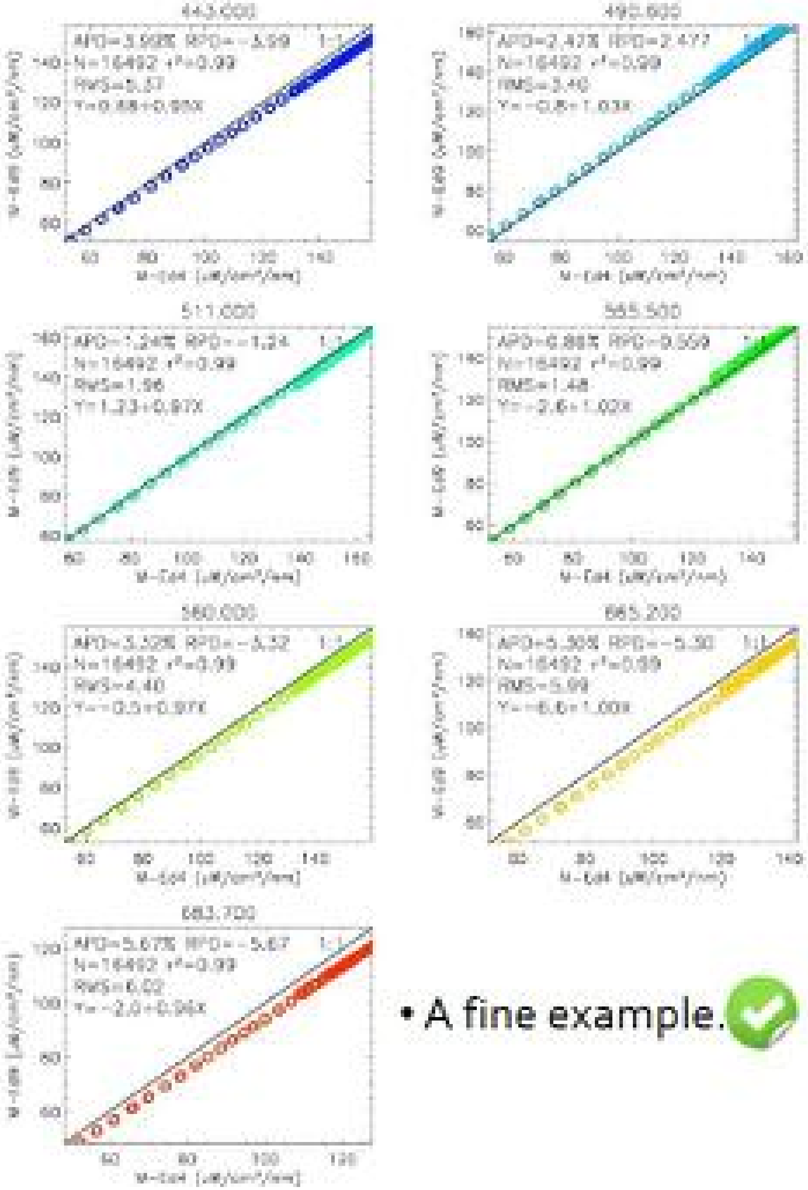
https://www.bs-ballasts.com/Workshop/N_Unzner/English/Halogen_Curve_big2.htm

The ocean environment



Morel/Antoine 1994, JPO

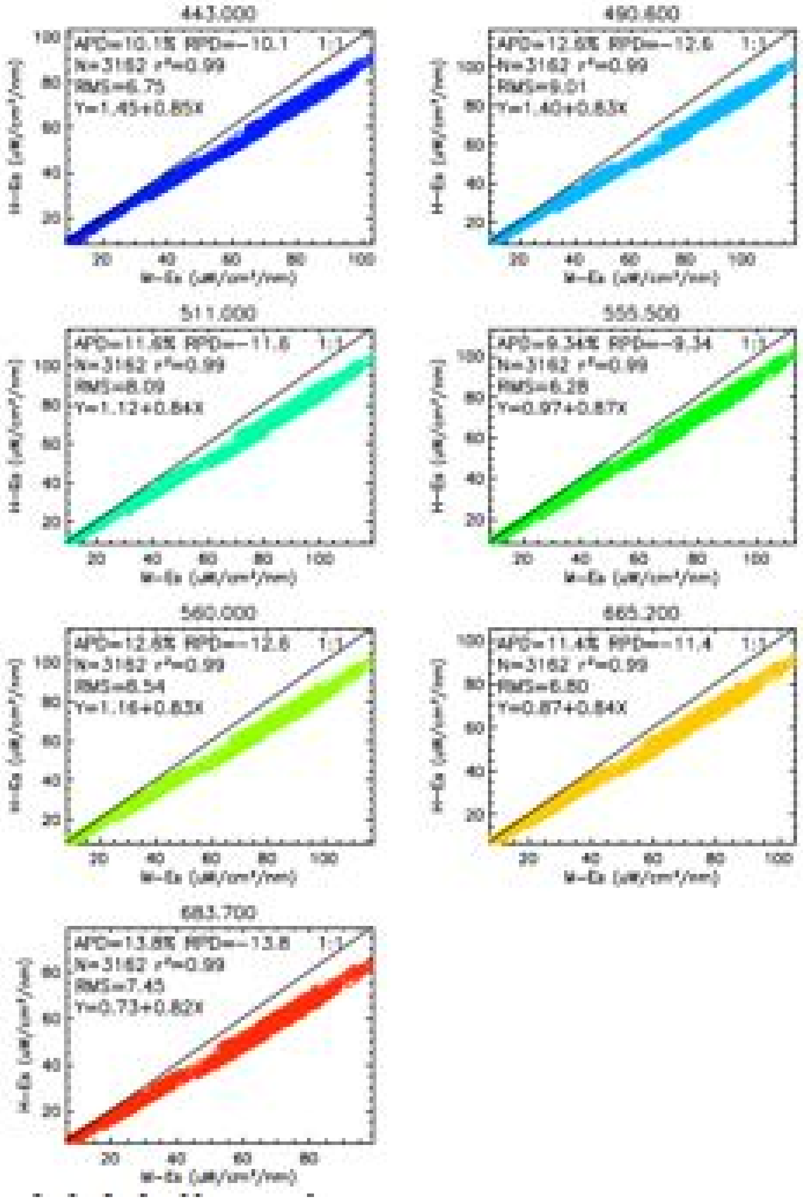
Independent checks



- A fine example.

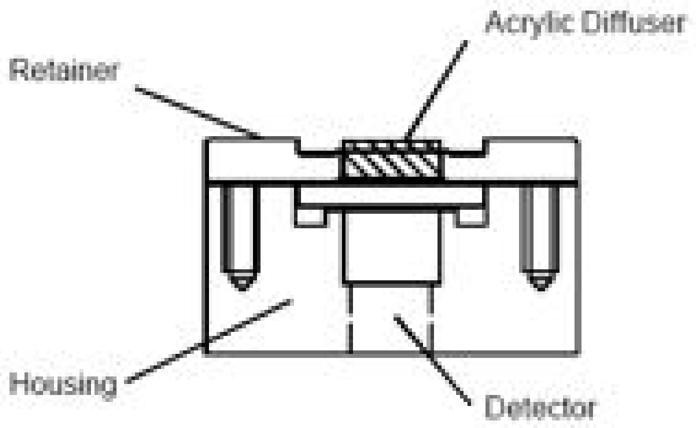
Intercomparison of instruments, useful to identify issues with the response of some of them

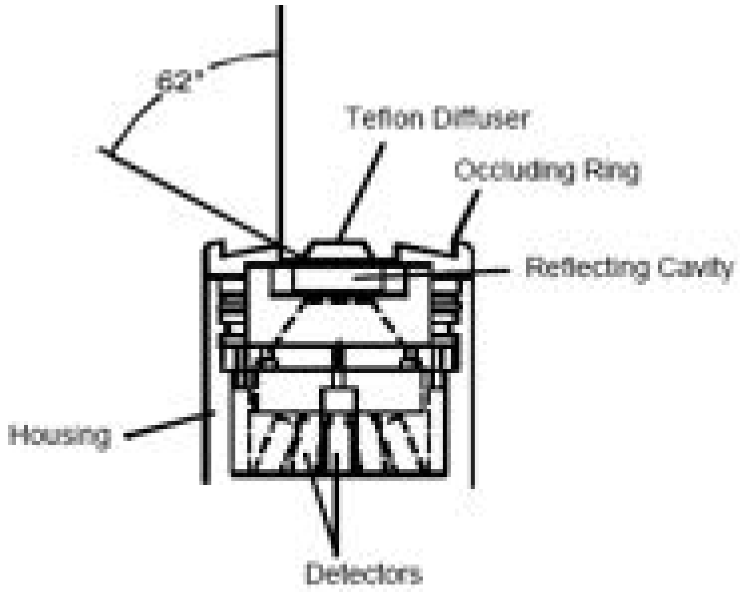
Independent checks

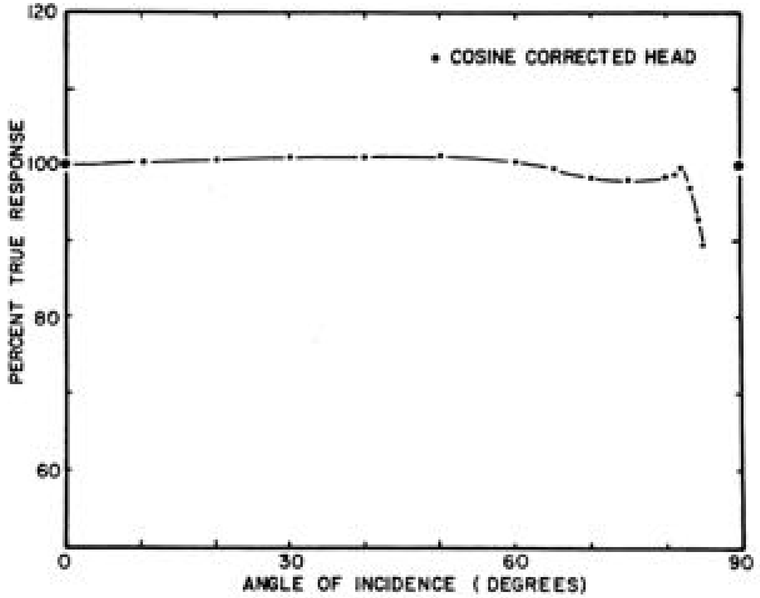


Intercomparison of instruments, useful to identify issues with the response of some of them

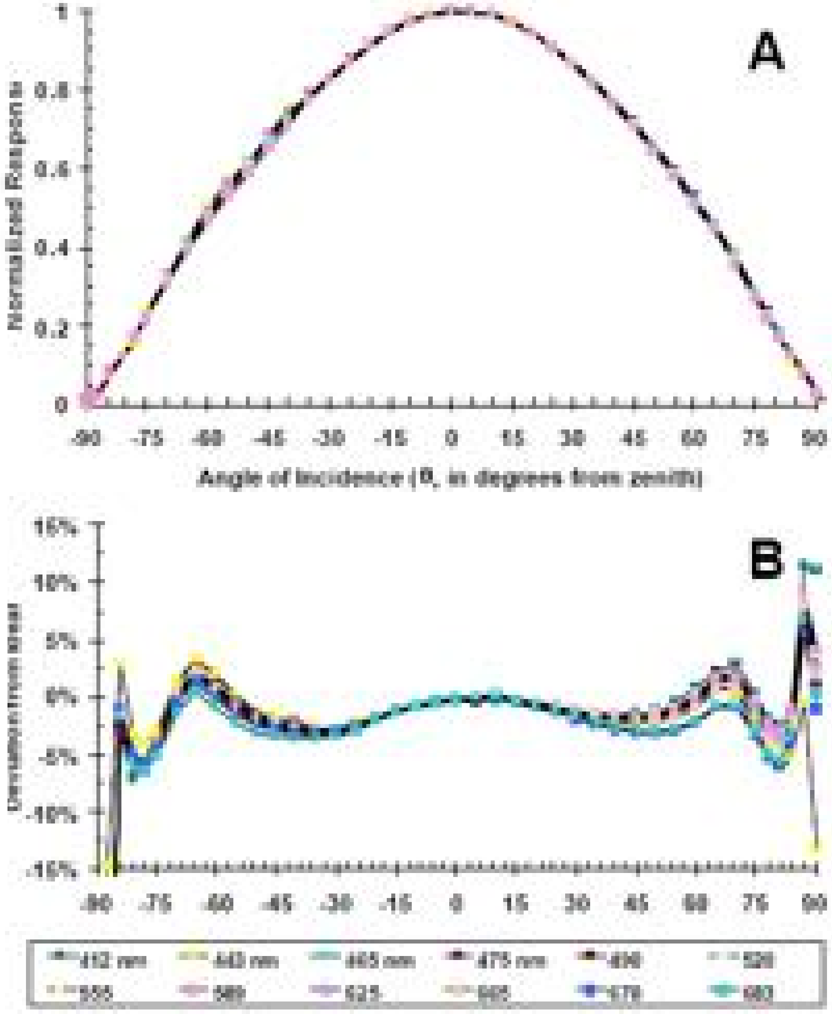
Cosine Response





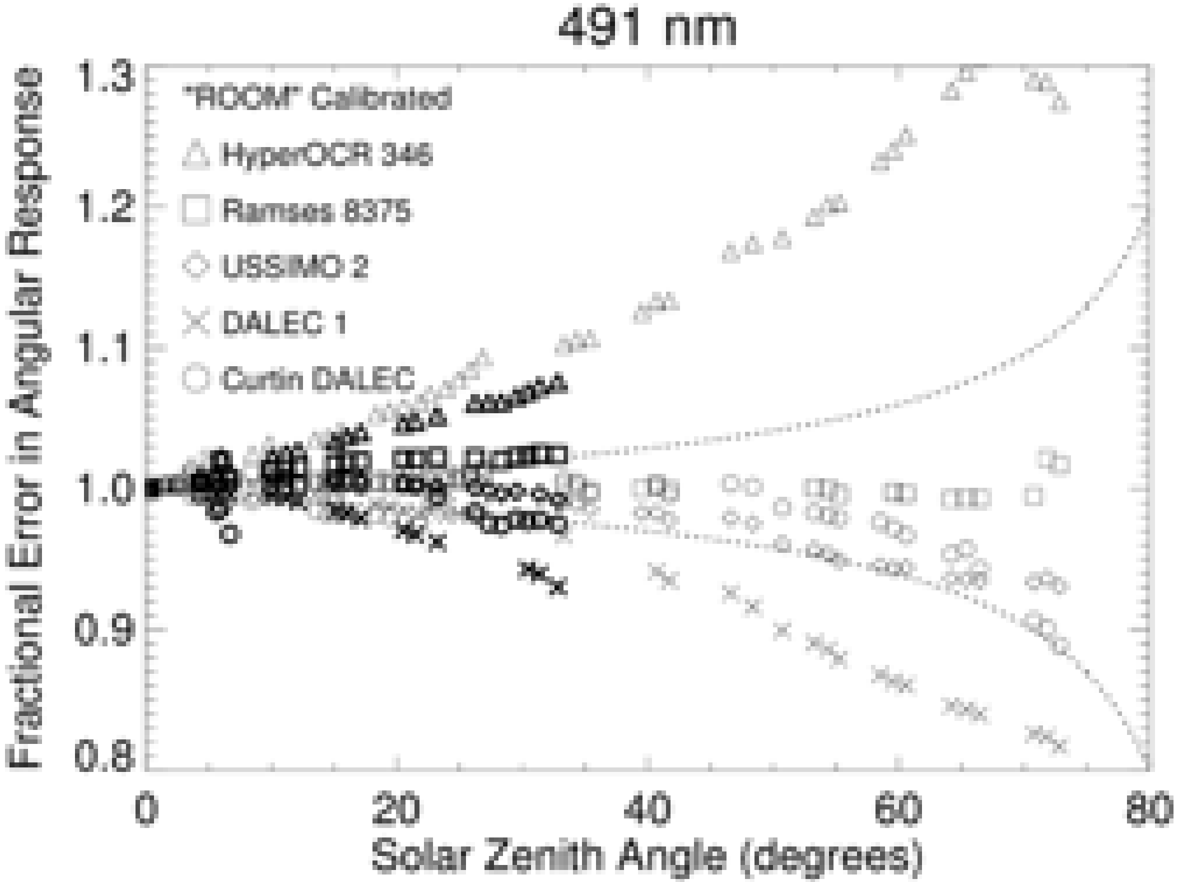


manufacturer's web page

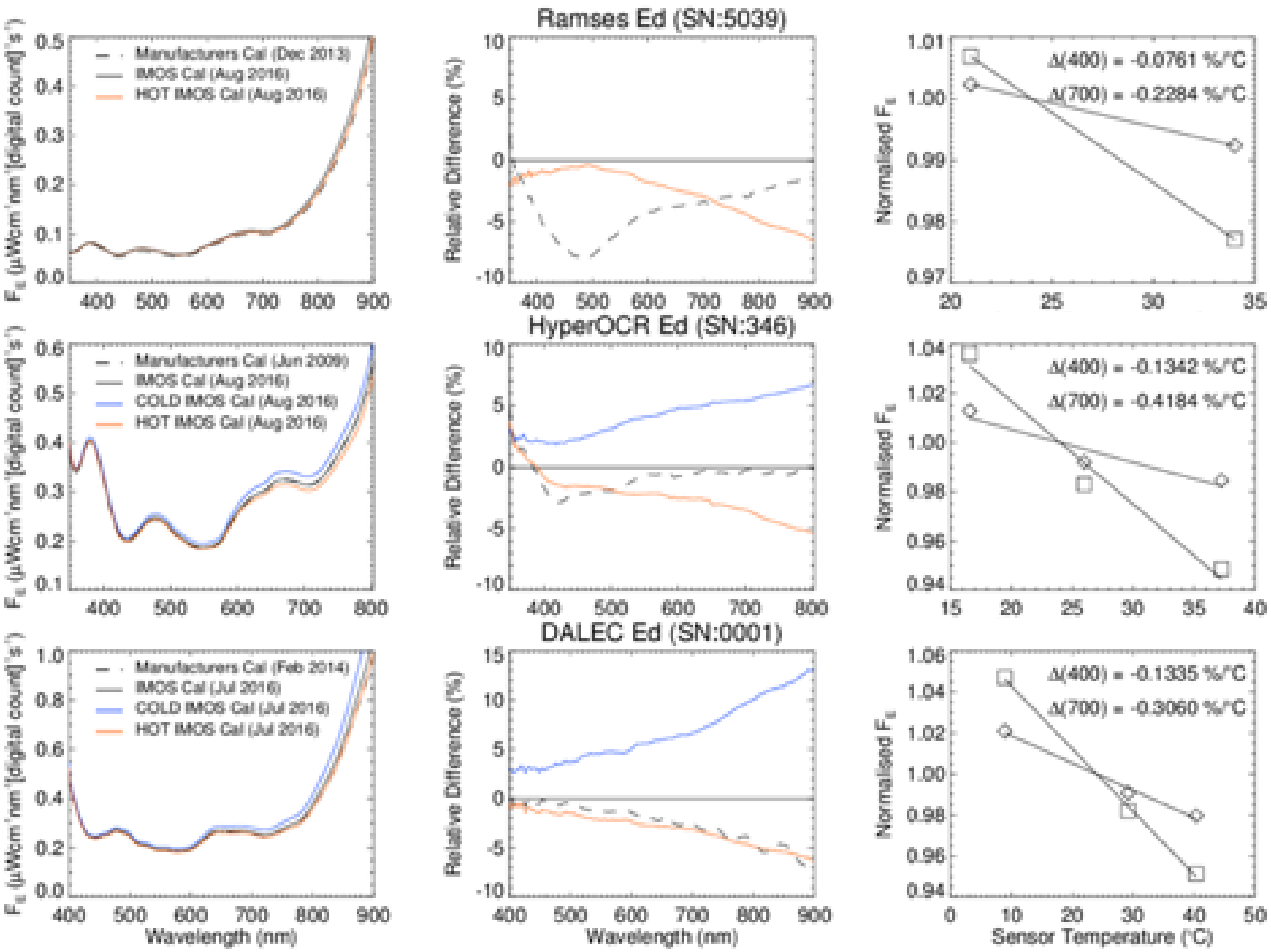


Morrow et al. 2000

Field Cosine Response



Temperature Dependency in Hyperspectral Radiometers



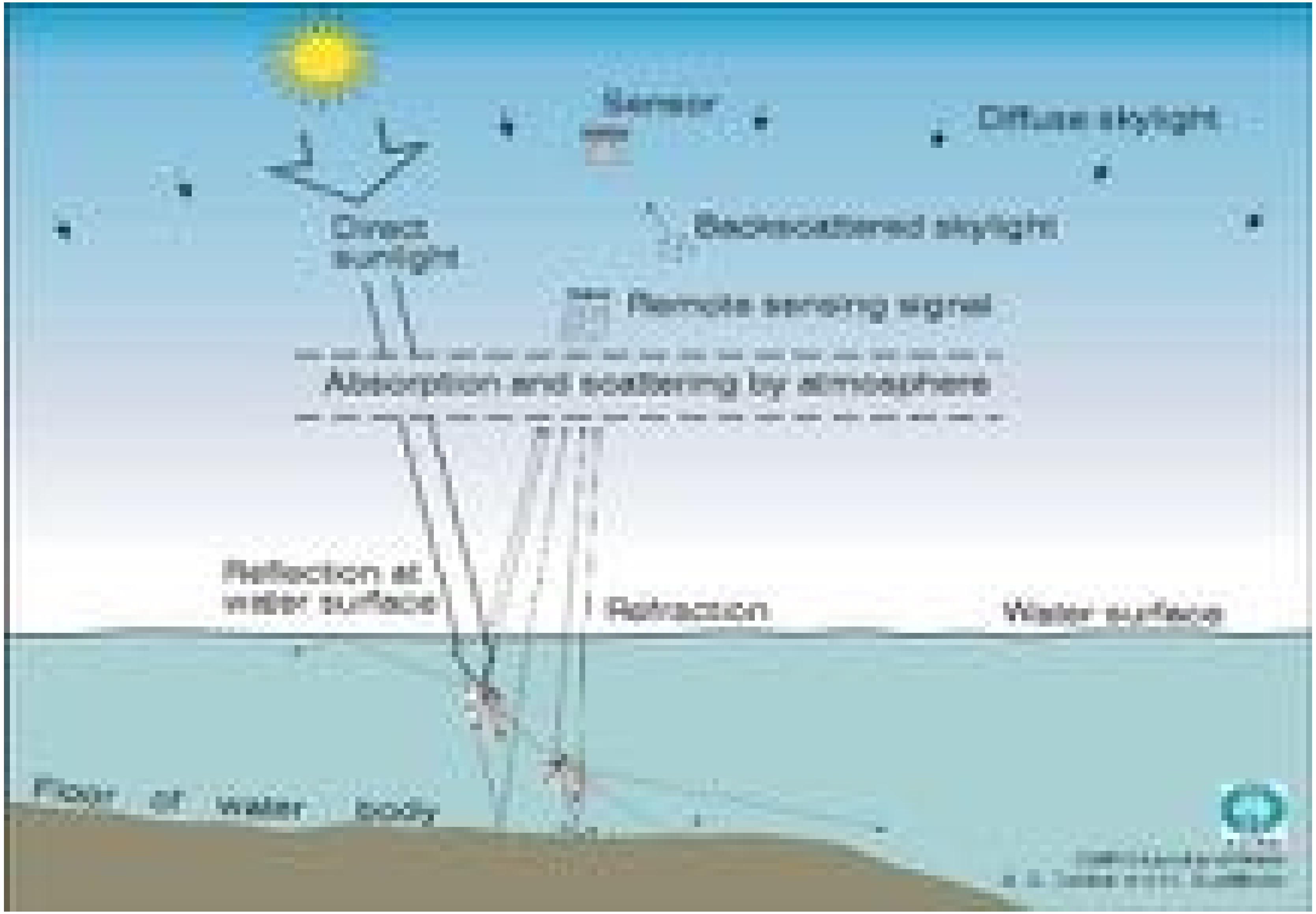
Also see, Zibordi et. al. 2017 jtech

Do not panic!

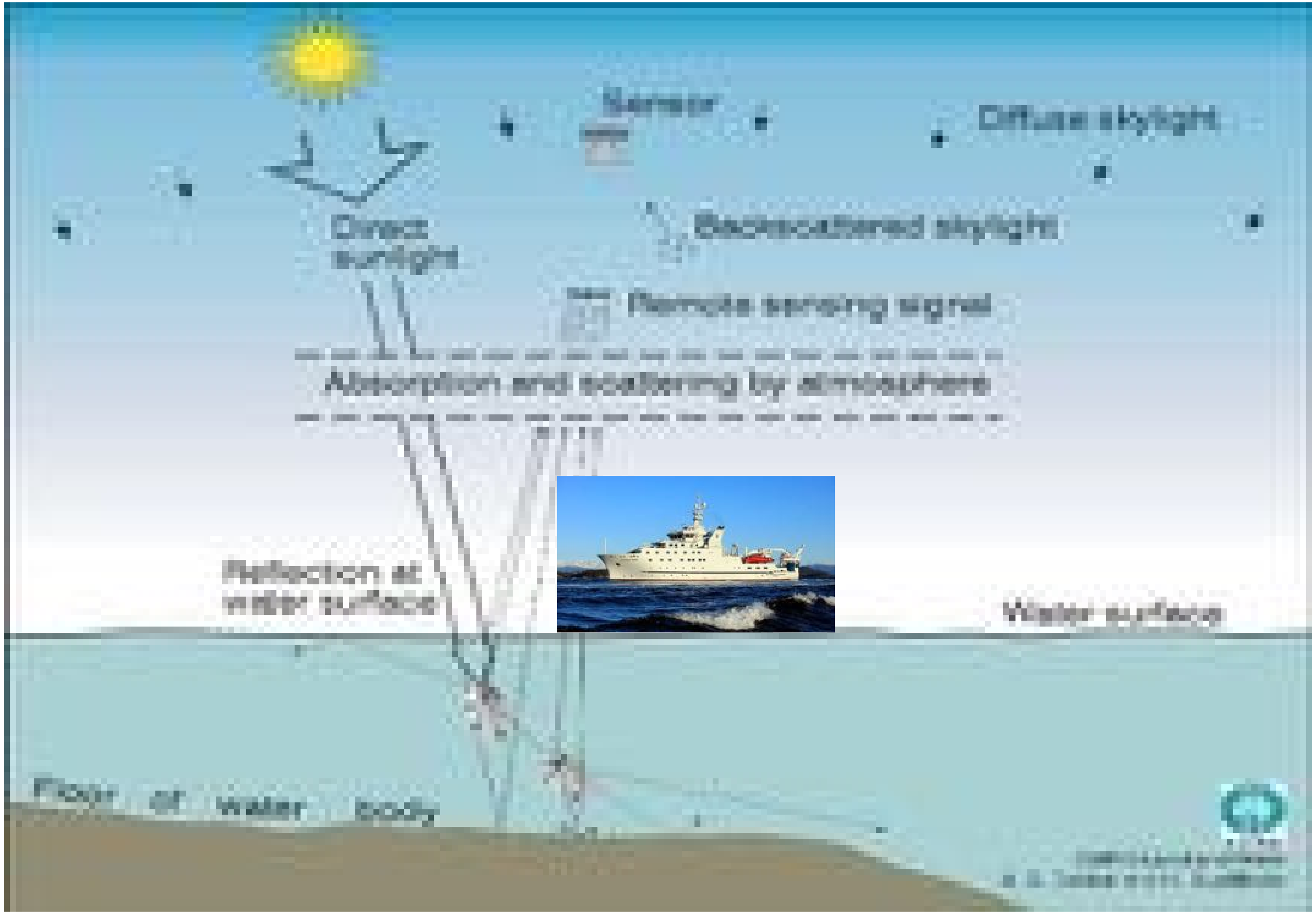
- The characterisation / calibration process is generally well performed by manufacturers (although you cannot necessarily blindly rely on this)
- Manufacturers will improve if we start discussing these issues in papers.
- Radiometric protocol documents to be updated to include new sensors?
- Add sensible error bars and move on!?
- The bigger the error bars, the easier disparate datasets can be said to “agree”

Deployment-related uncertainty sources

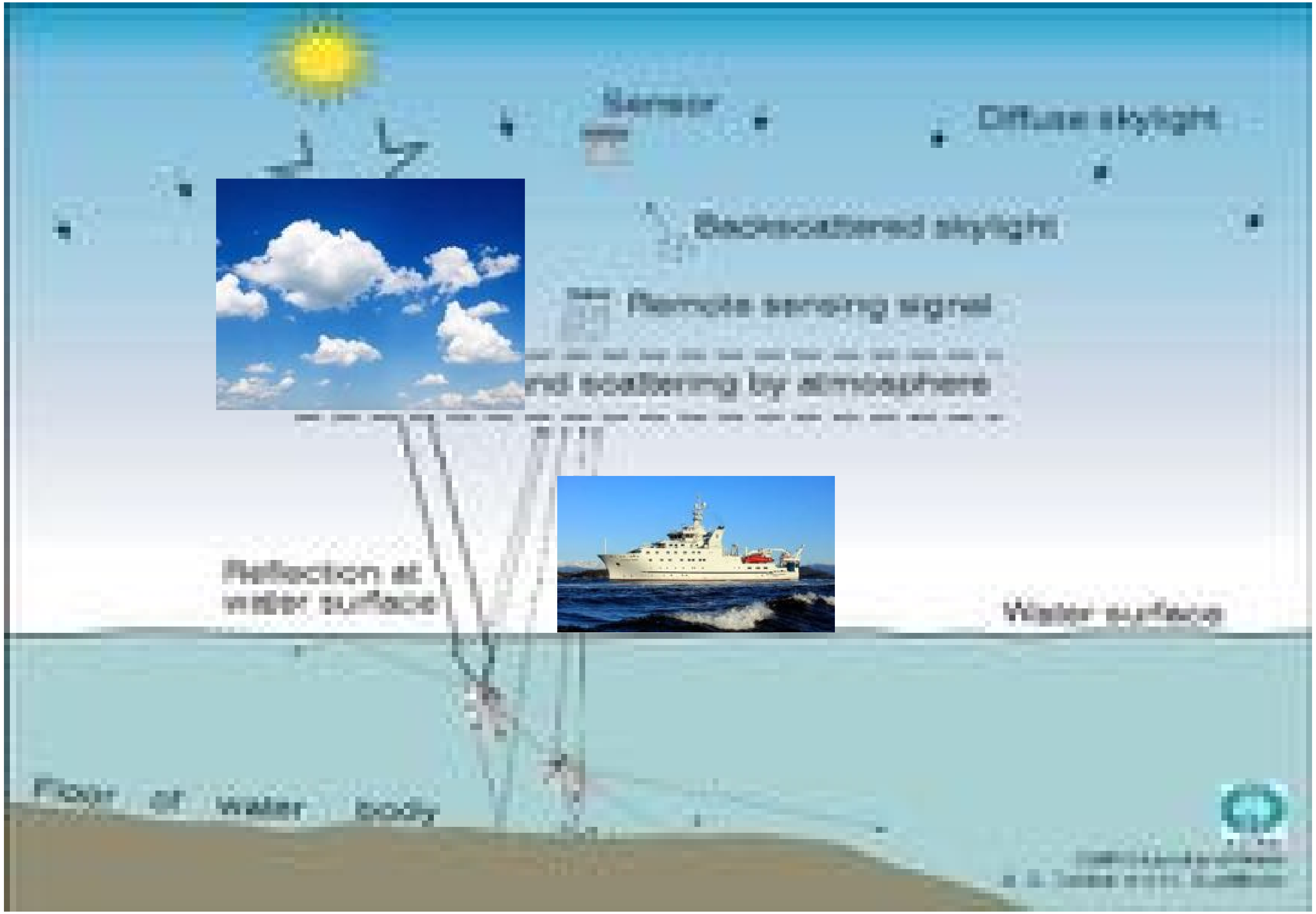
What makes radiometry measurement "special"?



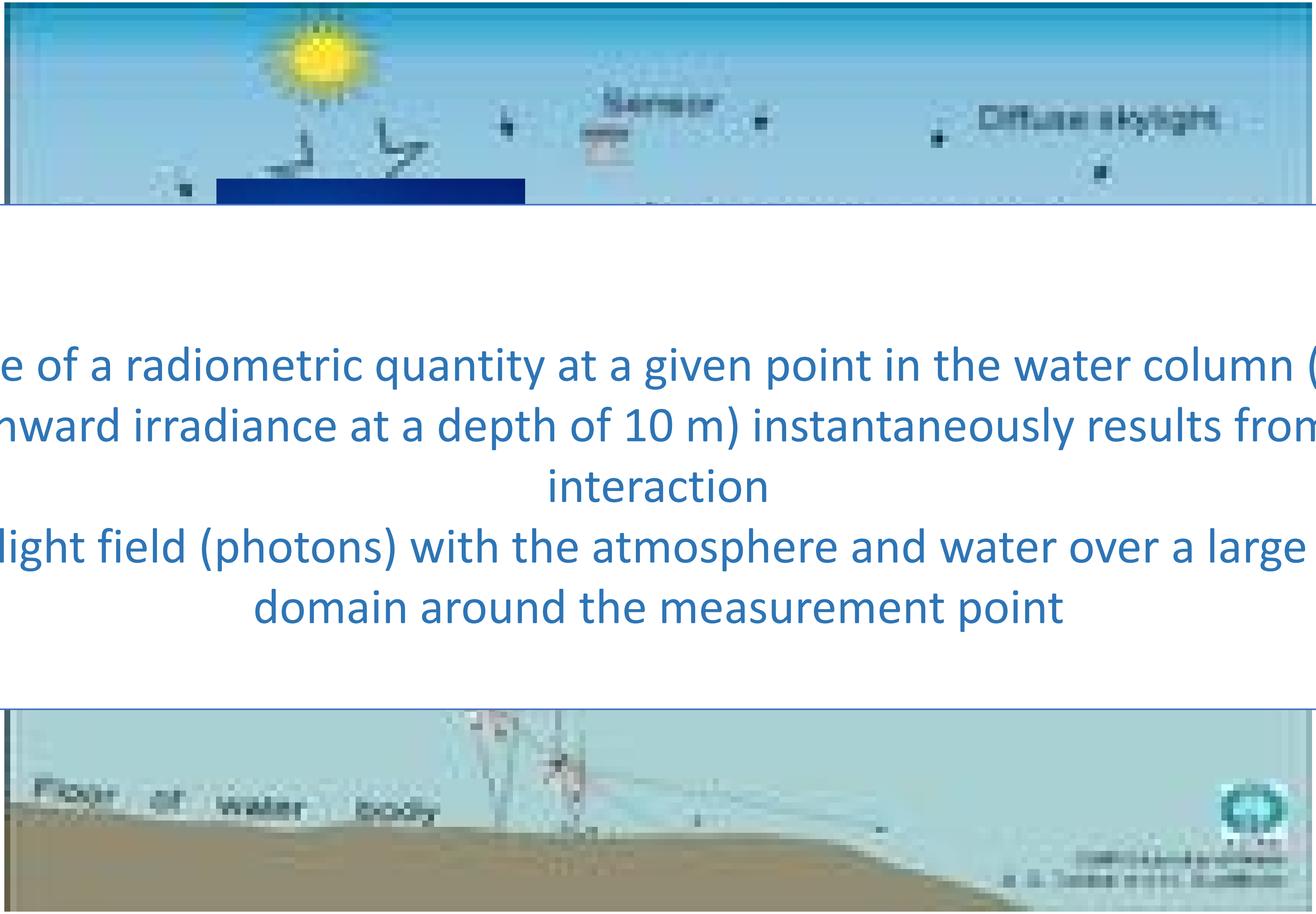
What makes radiometry measurement “special”?



What makes radiometry measurement "special"?



What makes radiometry measurement "special"?



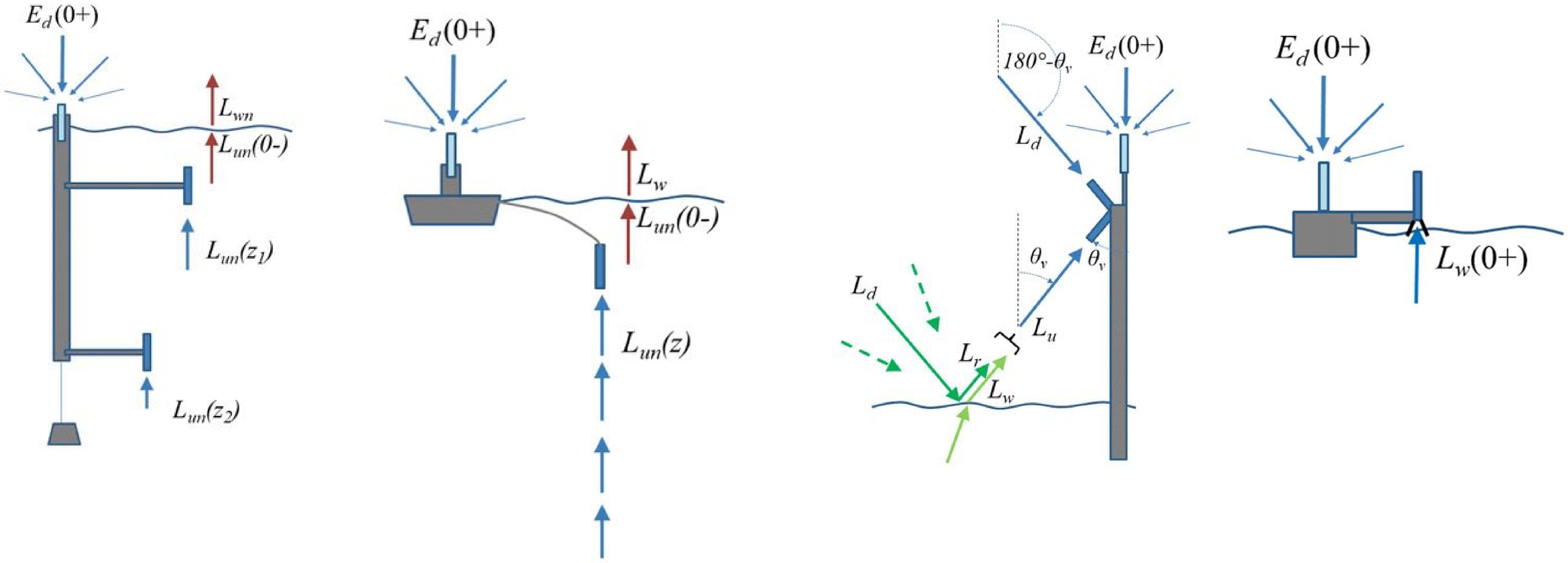
The value of a radiometric quantity at a given point in the water column (e.g., the downward irradiance at a depth of 10 m) instantaneously results from the interaction
of the light field (photons) with the atmosphere and water over a large spatial domain around the measurement point

Environment- and deployment-related Uncertainty sources in measurement of radiometric quantities

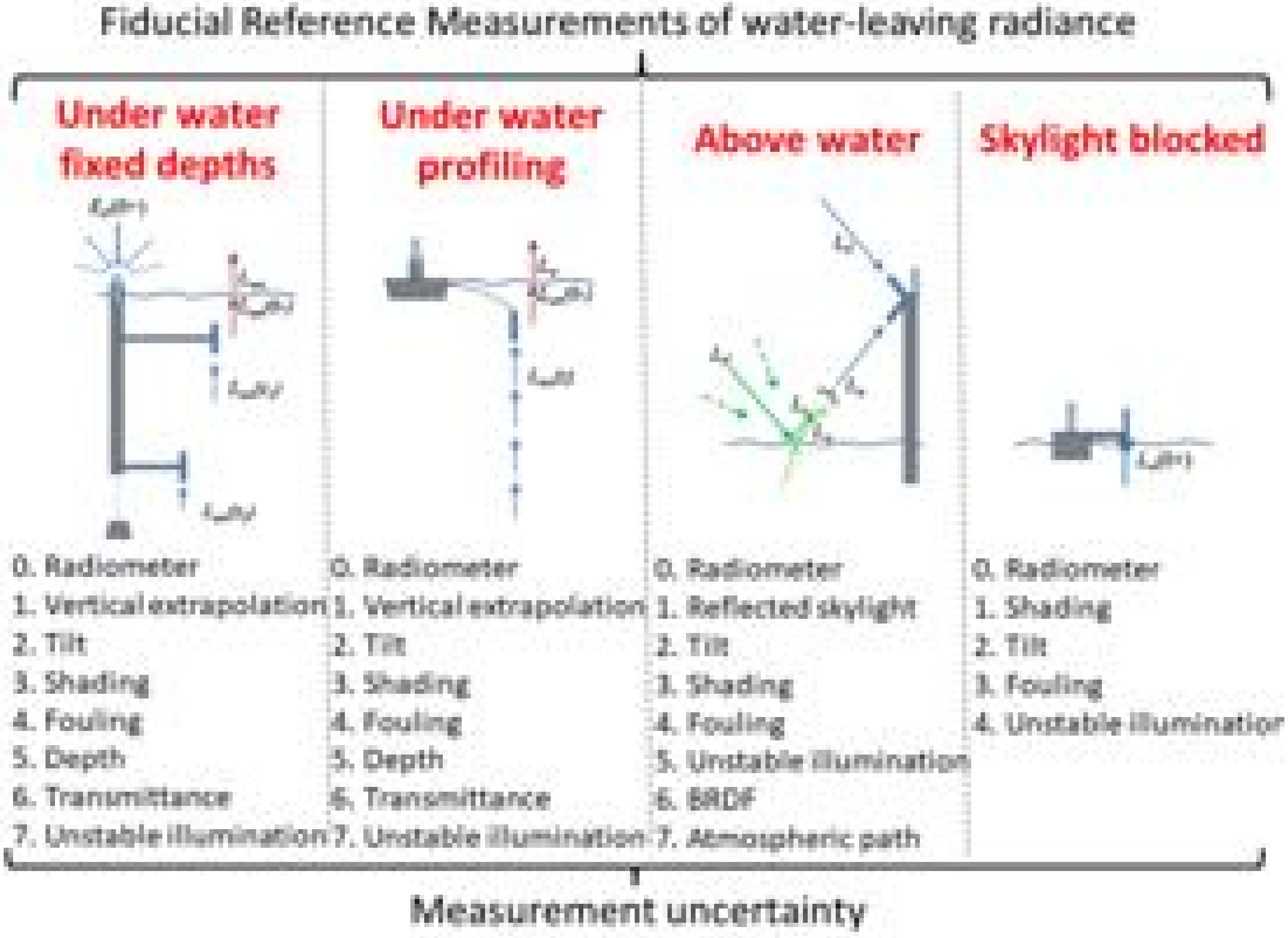
What to consider?

- **Weather**:
  - Is the sky could-free or overcast or cloudy? If the sky is cloud-free, how clear is it?
  - Is the sea rough? Can I see white caps? Significant sea spray?
- **Water**:
  - How clear or turbid the water is?
  - Can I suspect strong vertical stratification?
  - How homogeneous are the waters around me?
- **Platform and deployment**:
  - How big is the ship I'm working from? Can I move my instrument far enough from it?
  - Where can I install my deck E_s reference, if any? Is it gimbaled?
  - Can I easily communicate with the bridge? Do you have enough help on the deck?
- **Instrument:** (other than characterization/calibration considerations)
  - Did I clean the optical surfaces?
  - Was the instrument properly stored, e.g., away from excessive heating source?
  - Cables and connectors have been checked?

Various techniques to get to AOPs



Ruddick, K.G.; Voss, K.; Boss, E.; Castagna, A.; Frouin, R.; Gilerson, A.; Hieronymi, M.; Johnson, B.C.; Kuusk, J.; Lee, Z.; Ondrusek, M.; Vabson, V.; Vendt, R. A Review of Protocols for Fiducial Reference Measurements of Water-Leaving Radiance for Validation of Satellite Remote-Sensing Data over Water. Remote Sens. 2019, 11, 2198. https://doi.org/10.3390/rs11192198

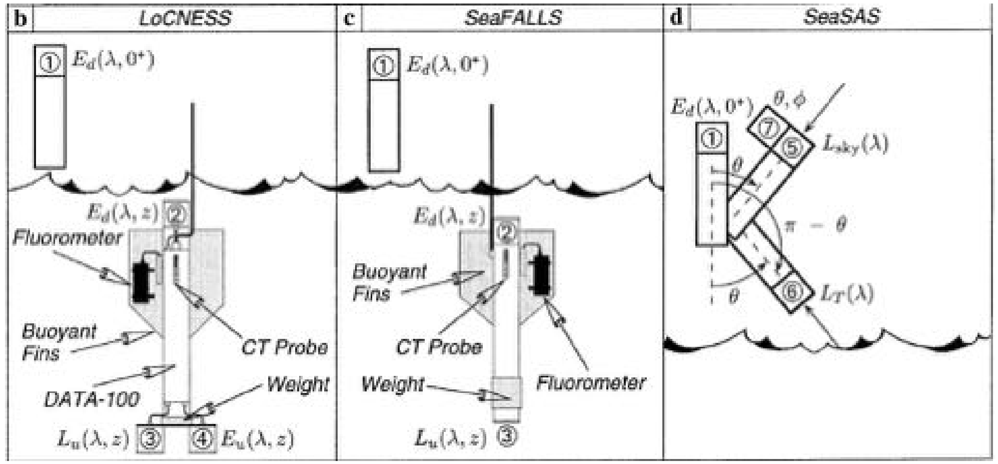


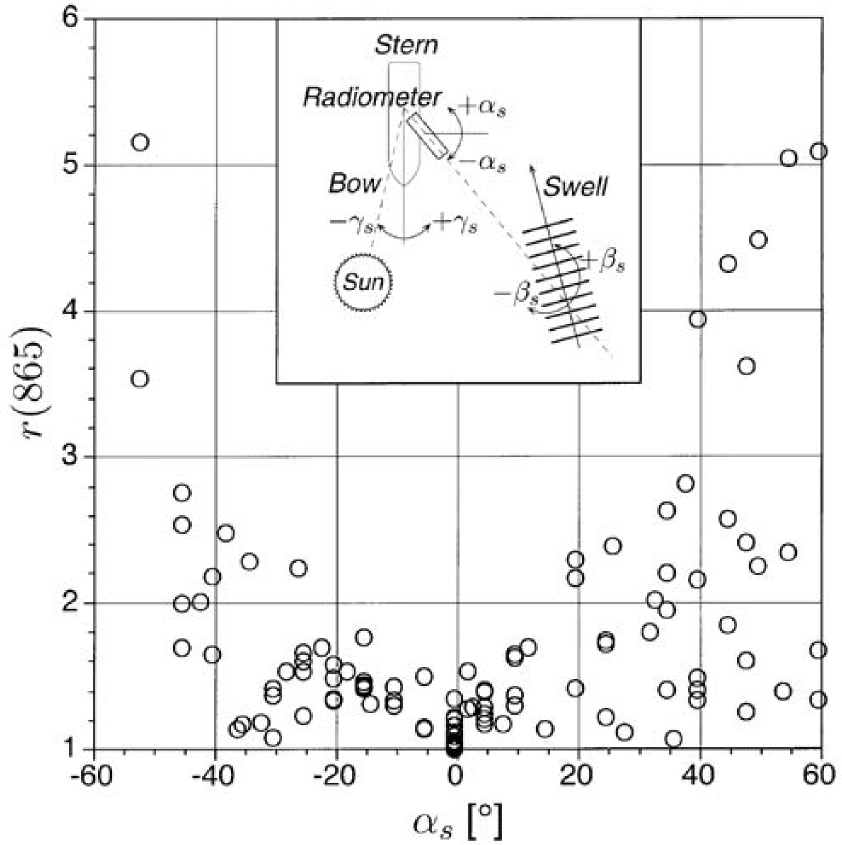
Ruddick, K.G.; Voss, K.; Boss, E.; Castagna, A.; Frouin, R.; Gilerson, A.; Hieronymi, M.; Johnson, B.C.; Kuusk, J.; Lee, Z.; Ondrusek, M.; Vabson, V.; Vendt, R. A Review of Protocols for Fiducial Reference Measurements of Water-Leaving Radiance for Validation of Satellite Remote-Sensing Data over Water. Remote Sens. 2019, 11, 2198. https://doi.org/10.3390/rs11192198

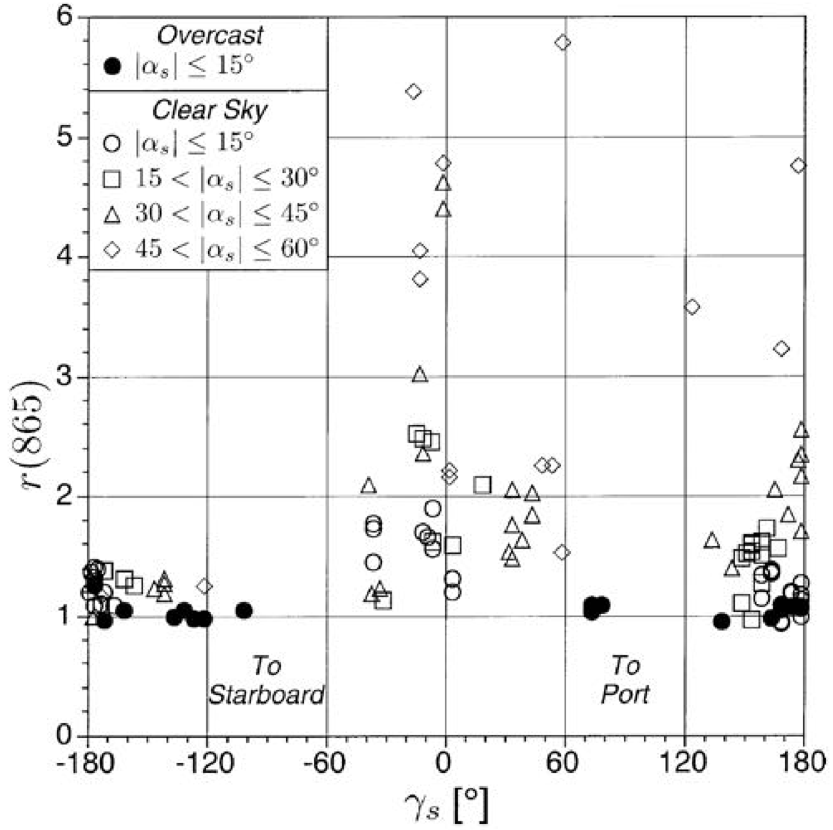
The platform

Hooker and Morel, JAOT, 2003

$$r(865) = \frac{L_T(865)/L_{sky}(865)}{\rho}$$

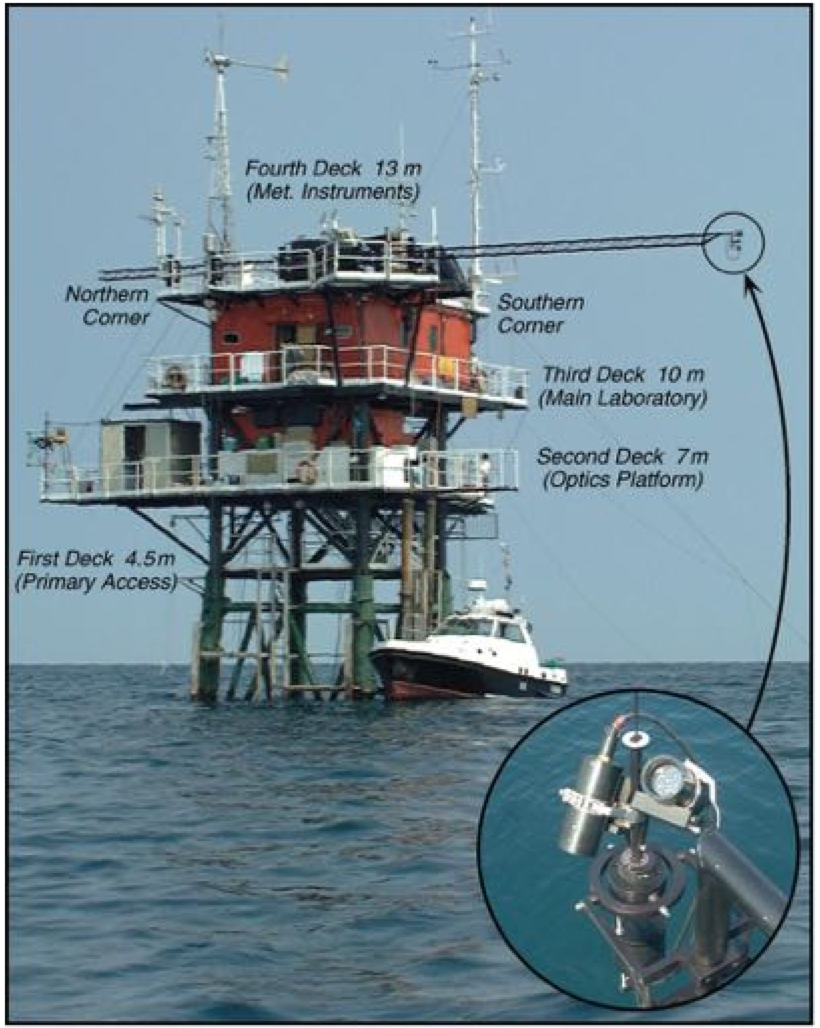






The platform

Hooker and Zibordi, Applied Optics 44(4), 2005



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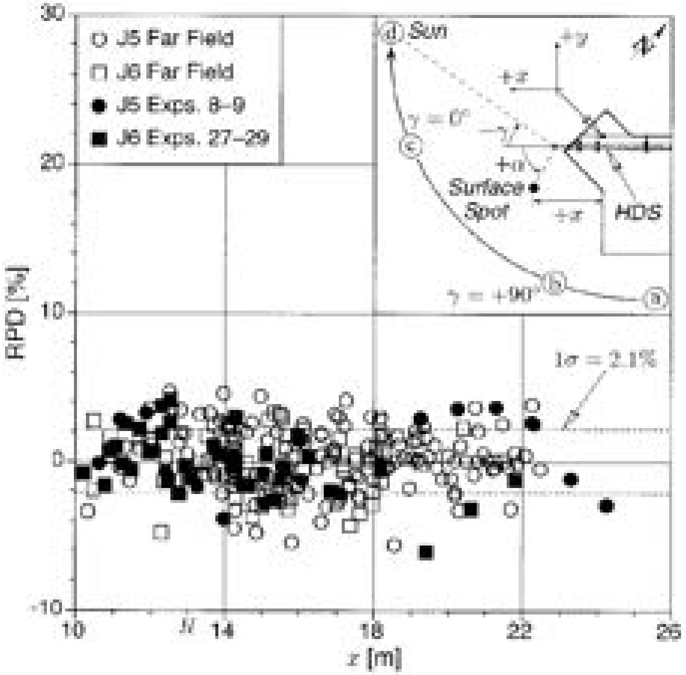
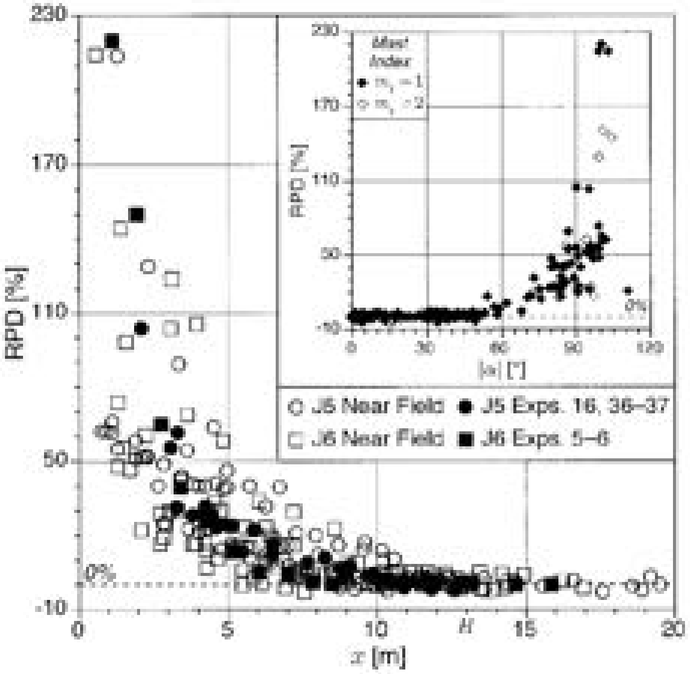


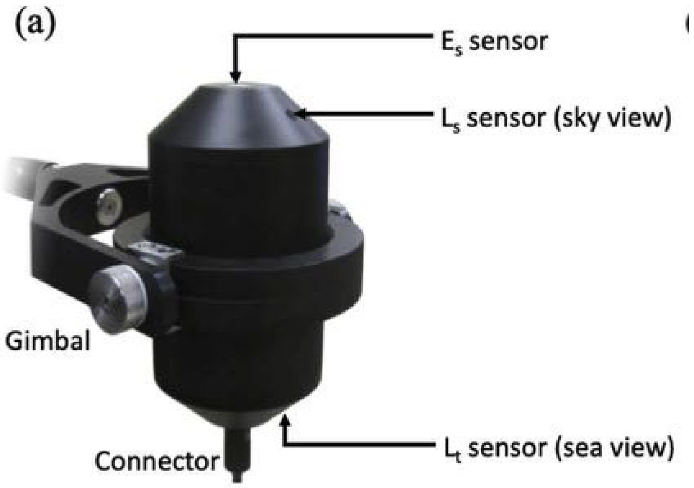


Data processing-related uncertainty sources

The following slides barely “scratch the surface”
They are only a few examples of typical data processing steps that can lead to significant uncertainties

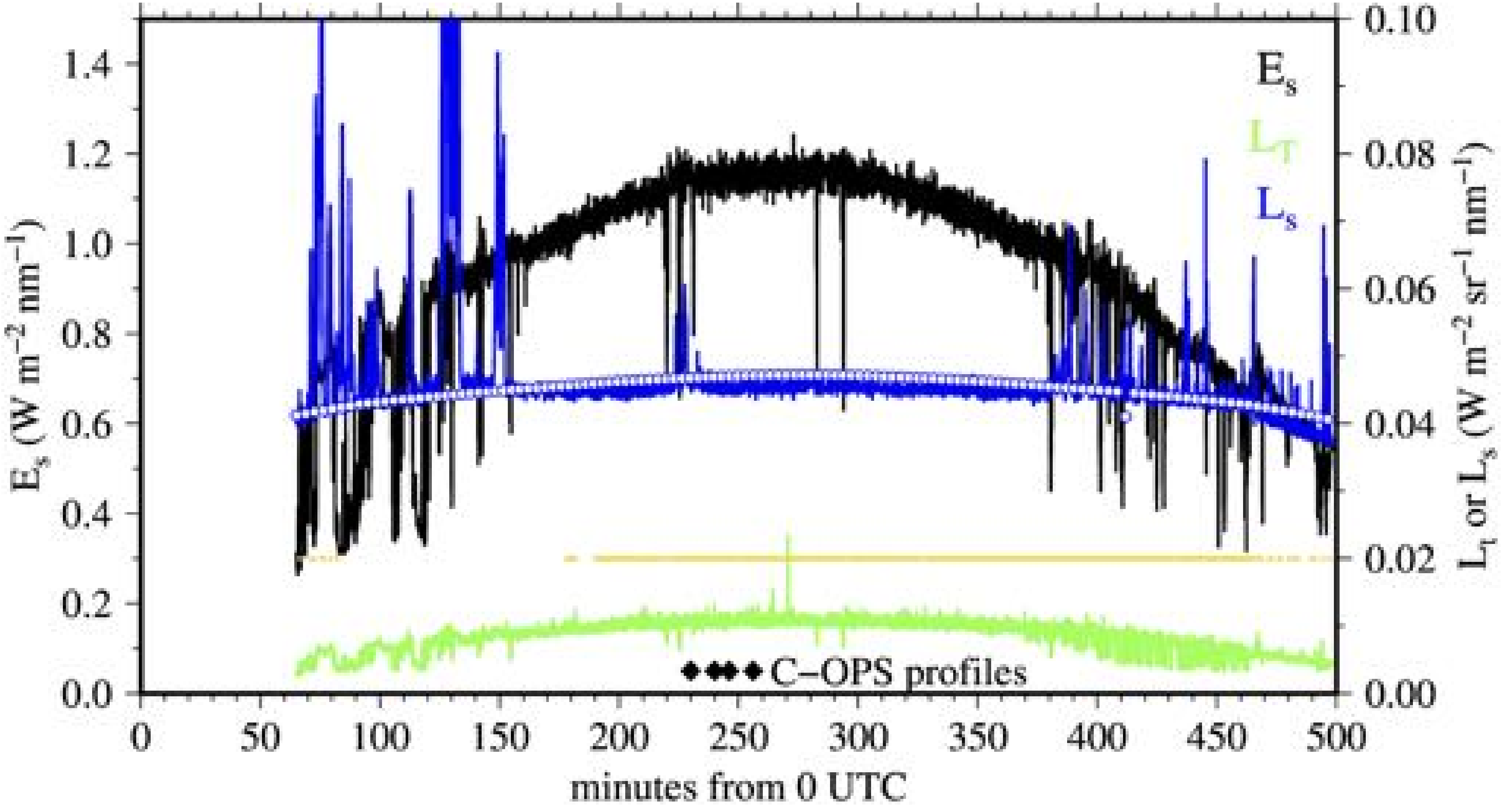
Data reduction

- Going from raw data to profiles (or time series) of the desired quantity (e.g., $L_u(z)$ or E_s).
  Applying calibration, and "filtering"

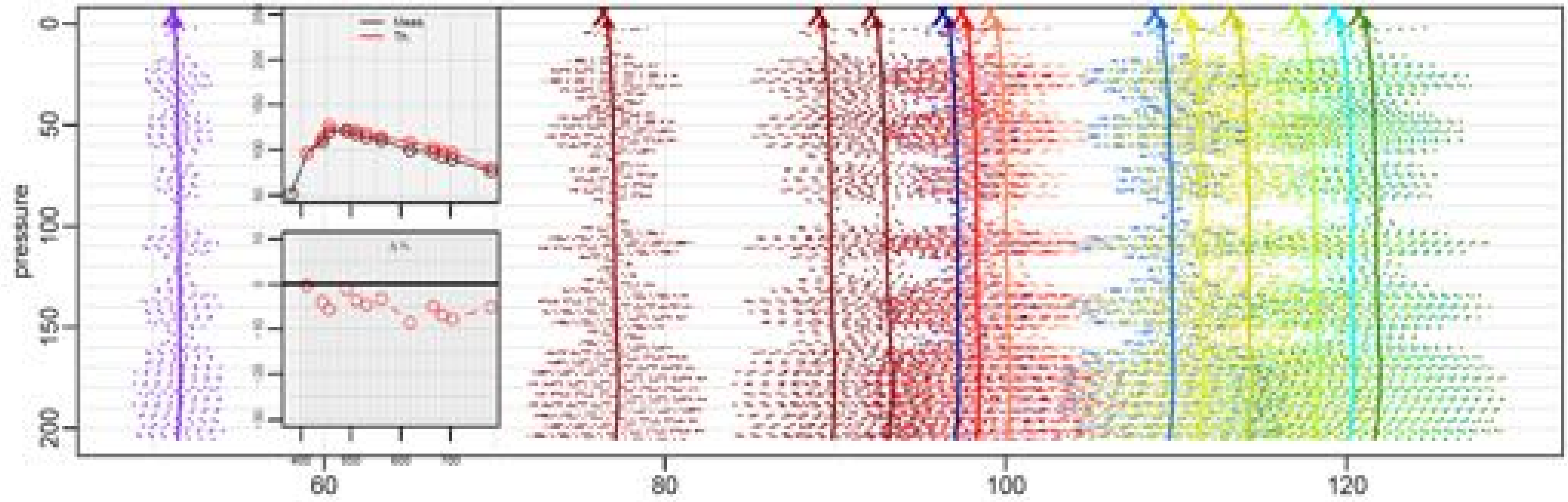


https://insitumarineoptics.com

Example of a DALEC record

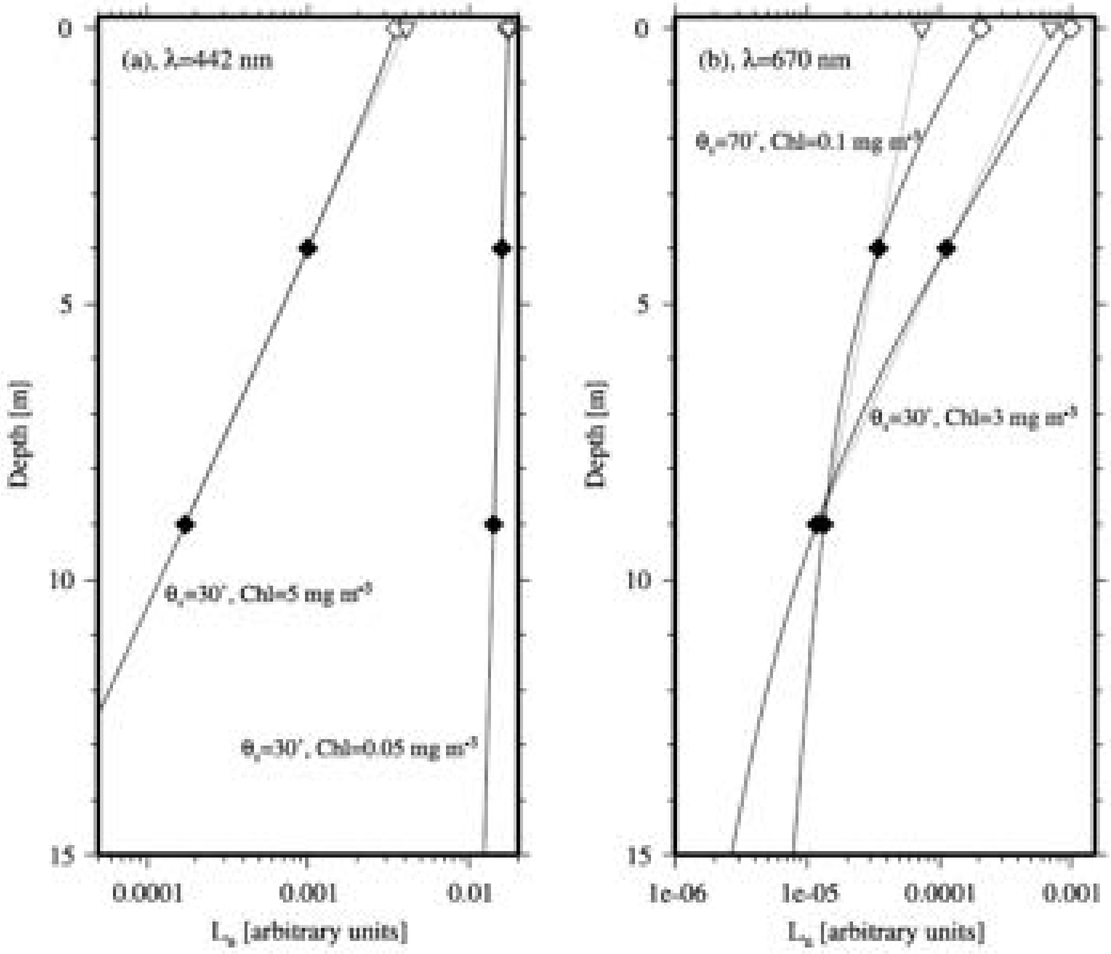


Getting E_s from a non-gimbaled sensor

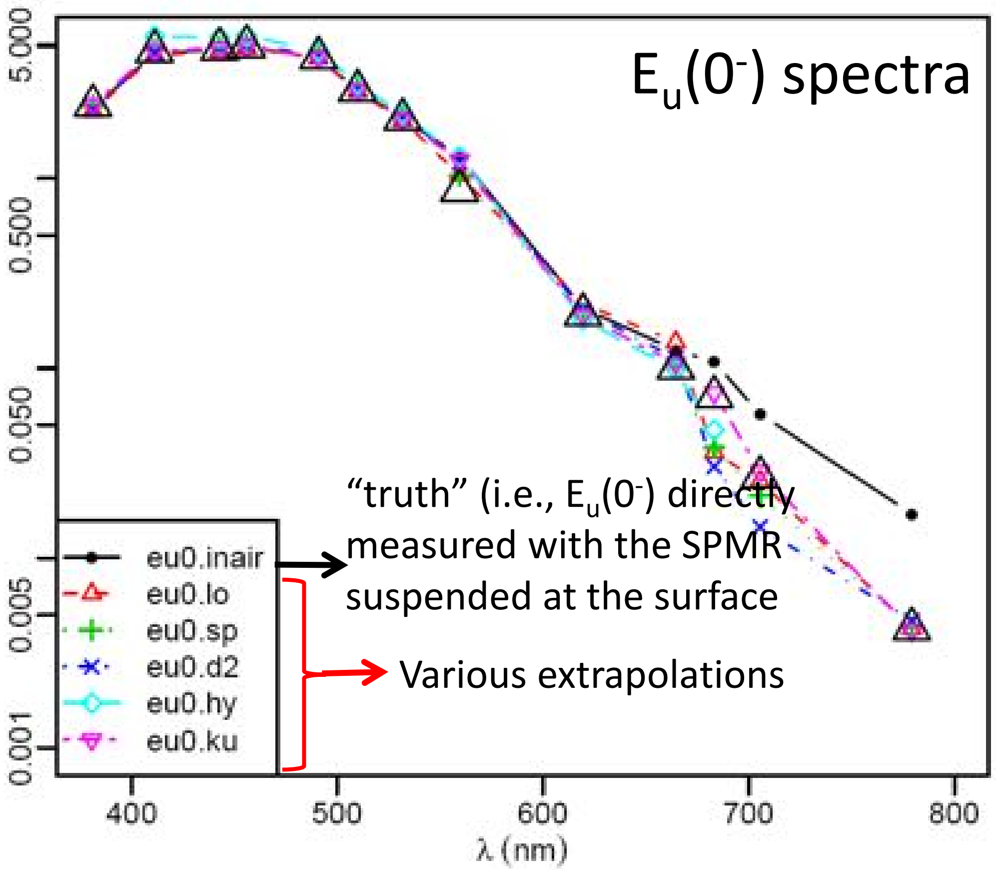


The $E_s(\lambda)$ spectrum can be reasonably well simulated (need to know date, time, lat, long, and atmosphere parameters such as pressure, aerosol optical thickness, wind speed, ozone…)

Extrapolating to “0-”

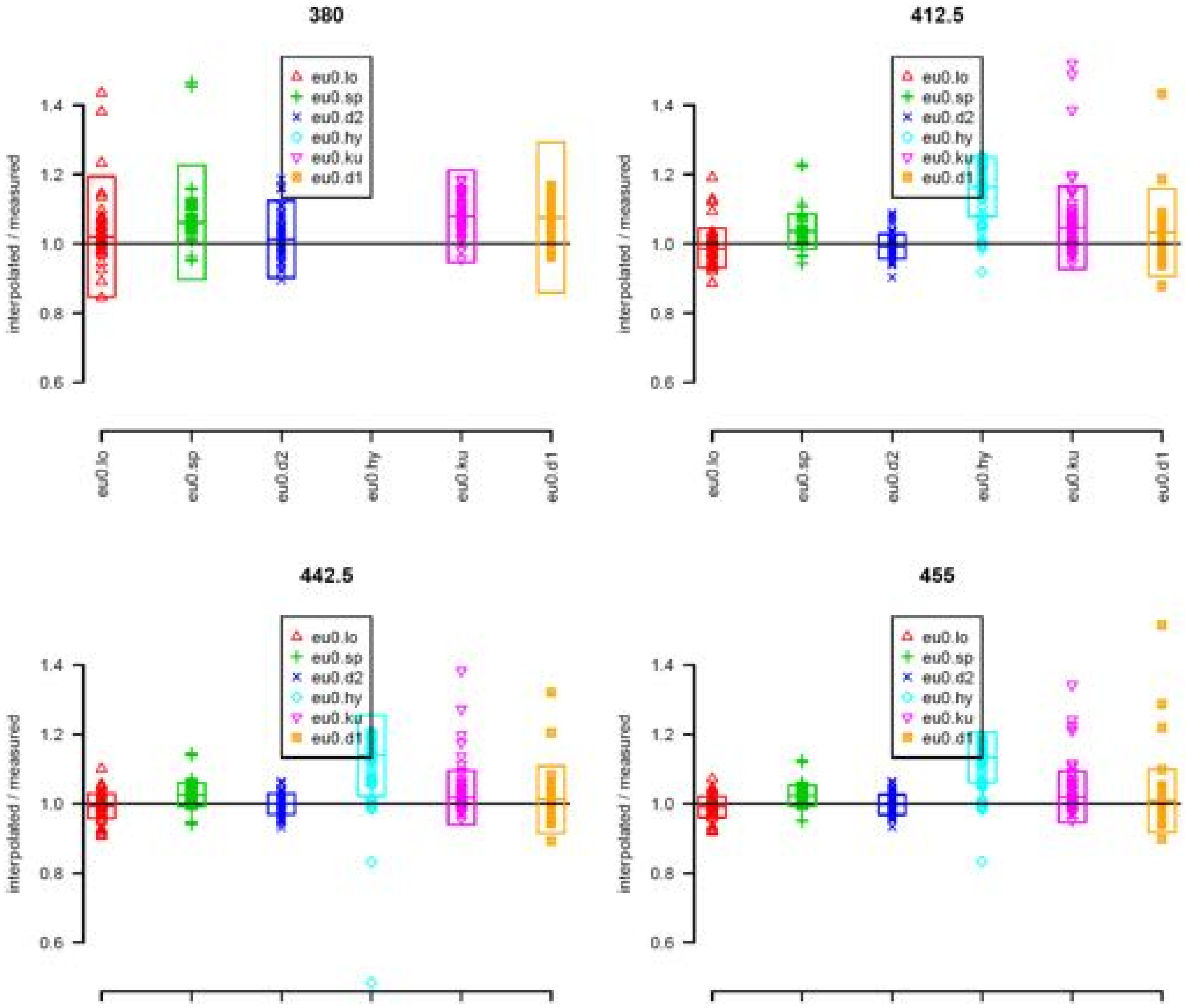


An example for fixed-depth measurements
(Antoine et al., JGR, VOL. 113, C07013, doi:10.1029/2007JC004472)



An example for profile measurements
(unpublished data from BOUSSOLE)

Extrapolating to “0-”



(unpublished data from BOUSSOLE)

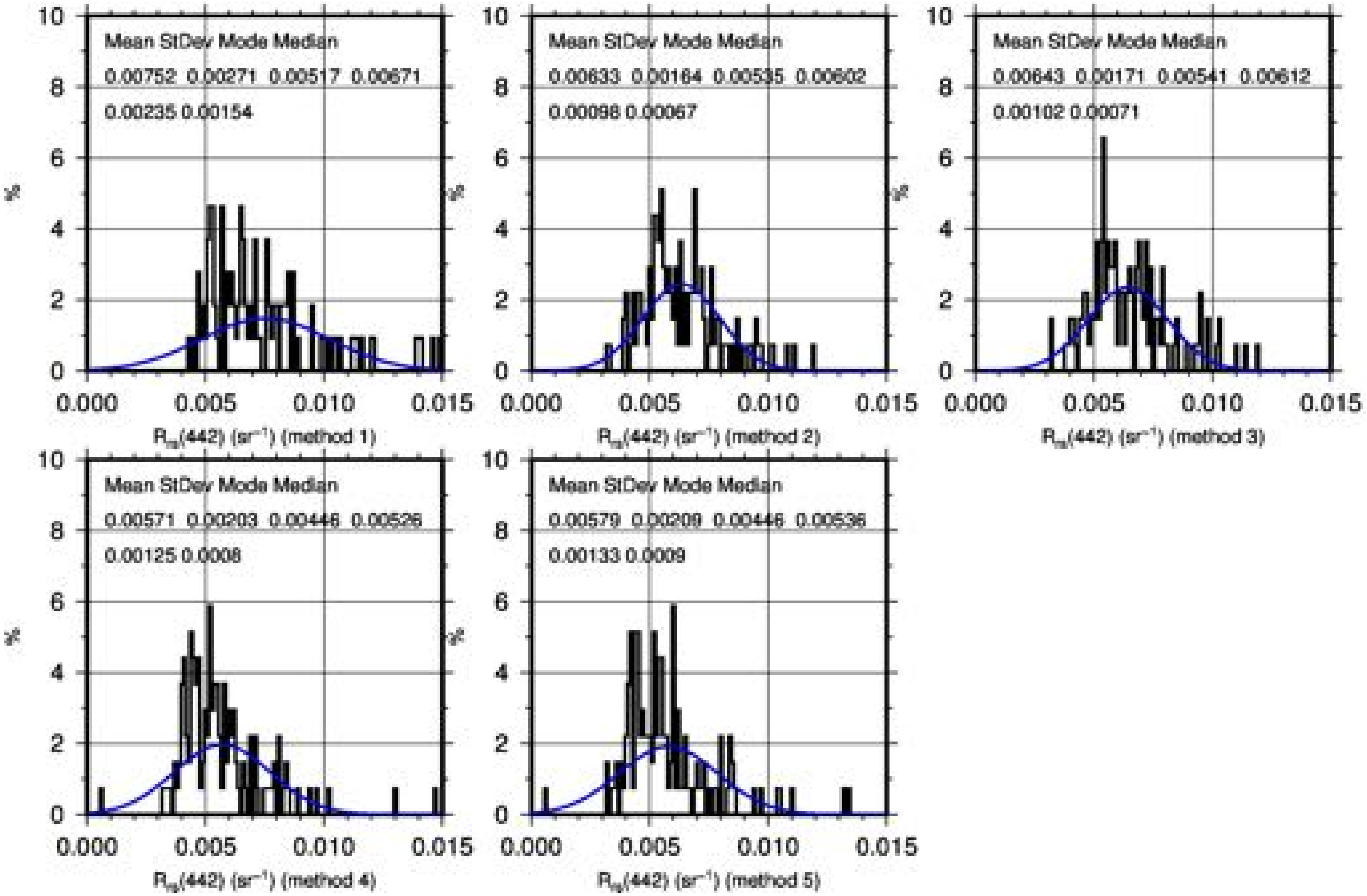
Conclusion / message

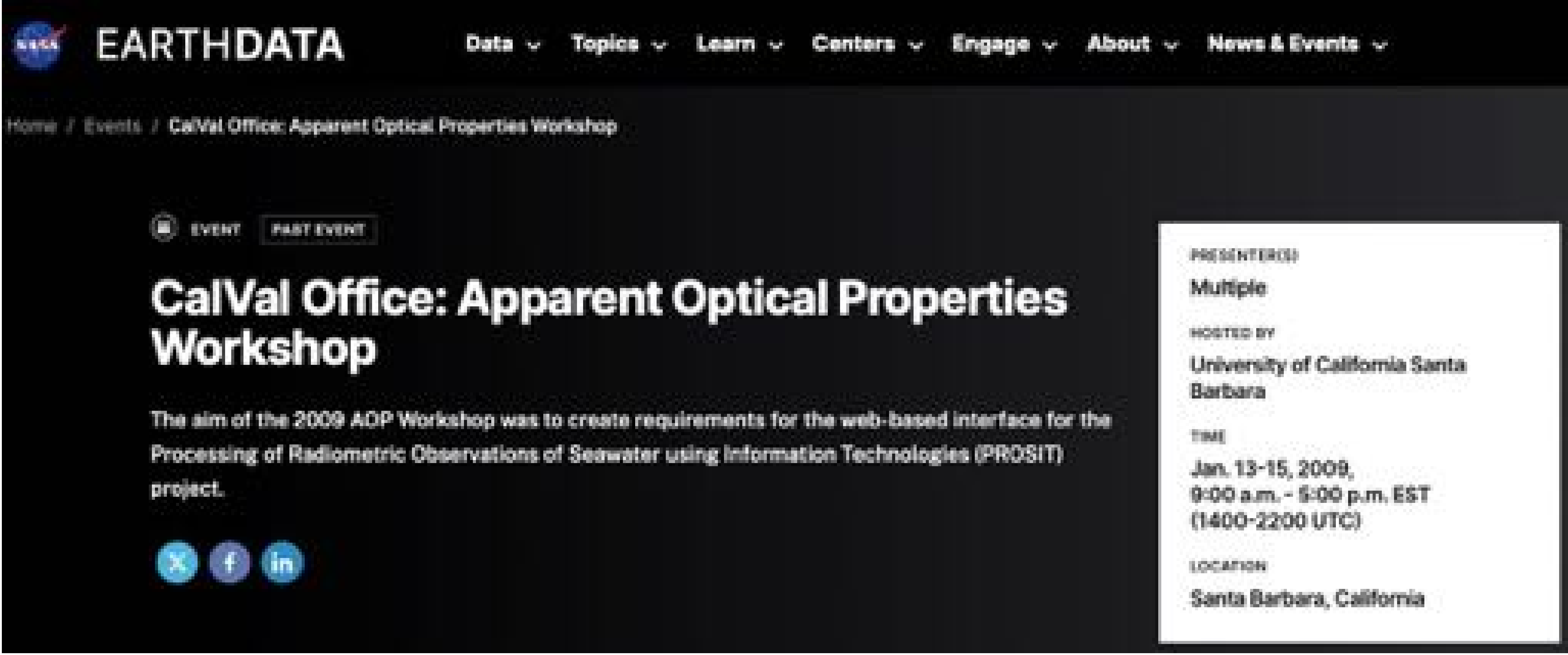
- Extrapolation technique matters!
- There is definitely more to be done in that space to improve the quality of our data sets

Extrapolating to “0-”

Method	E_s	K_d
RRS1	**Surface** E_s measurements, corrected for cosine response. Spectral FOR loop median of data with less than 5 degree tilt	Full Cast model fit of $E_d(z-)/(0.96*E_s) = \exp(\mathbf{K_d}*z)$
RRS2	**Surface** E_s measurements, corrected for cosine response, **combined with subsurface data** (corrected for transmission). Double parameter exponential fit yielding E_s and K_d **using full cast**	Full Cast model fit of $E_d(z-)=(0.96*E_s) * \exp(\mathbf{K_d}*z)$
RRS3	**Surface** E_s measurements, corrected for cosine response, **combined with subsurface data** (corrected for transmission). Double parameter exponential fit yielding E_s and K_d using only R_{rs} depths for extrapolation **(initial 1/K_d estimate)**	Re-run model fit of $E_d(z-)=(0.96*E_s) * \exp(\mathbf{K_d}*z)$ using data from 1/K_d or shallower
RRS4	**Subsurface** Irradiance data (corrected for transmission). Double parameter exponential fit yielding E_s and K_d **using full subsurface cast**	Full Cast model fit of $E_d(z-)=(0.96*E_s) * \exp(\mathbf{K_d}*z)$
RRS5	**Subsurface** Irradiance data (corrected for transmission). Double parameter exponential fit yielding E_s and K_d **(initial 1/K_d estimate)**	Re-run model fit of $E_d(z-)=(0.96*E_s) * \exp(K_d*z)$ using data from 1/K_d or shallower

Extrapolating to "0-"



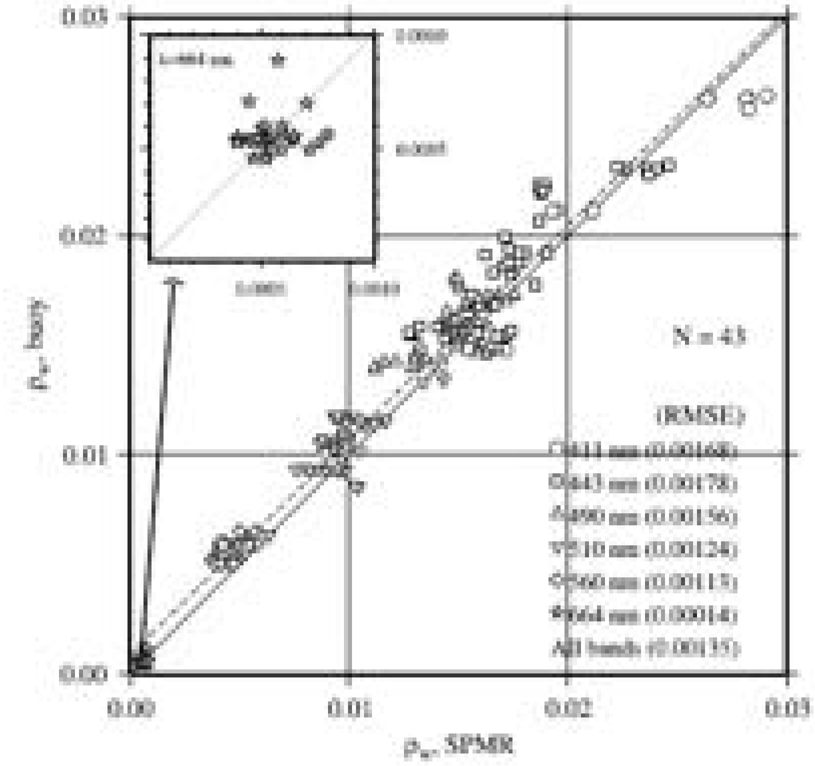


https://www.earthdata.nasa.gov/events/calval-office-apparent-optical-properties-workshop

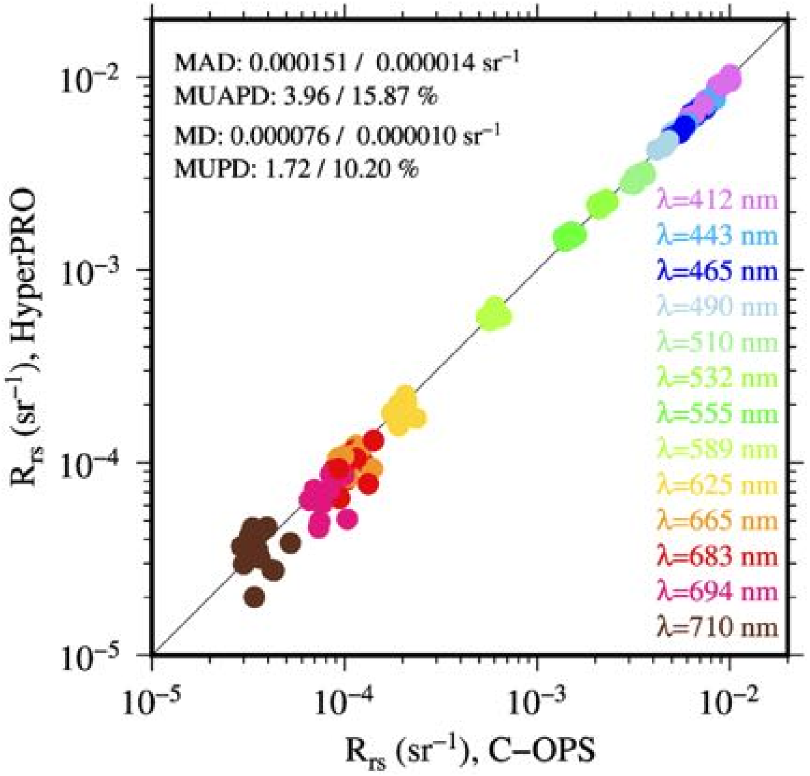
>20 Presentations from various field programs, about how they deal with measurements, protocols, data QC and processing

Comparing data sets

Deriving the same quantity, e.g., R_{rs}, derived from simultaneous radiometry measurements using different techniques

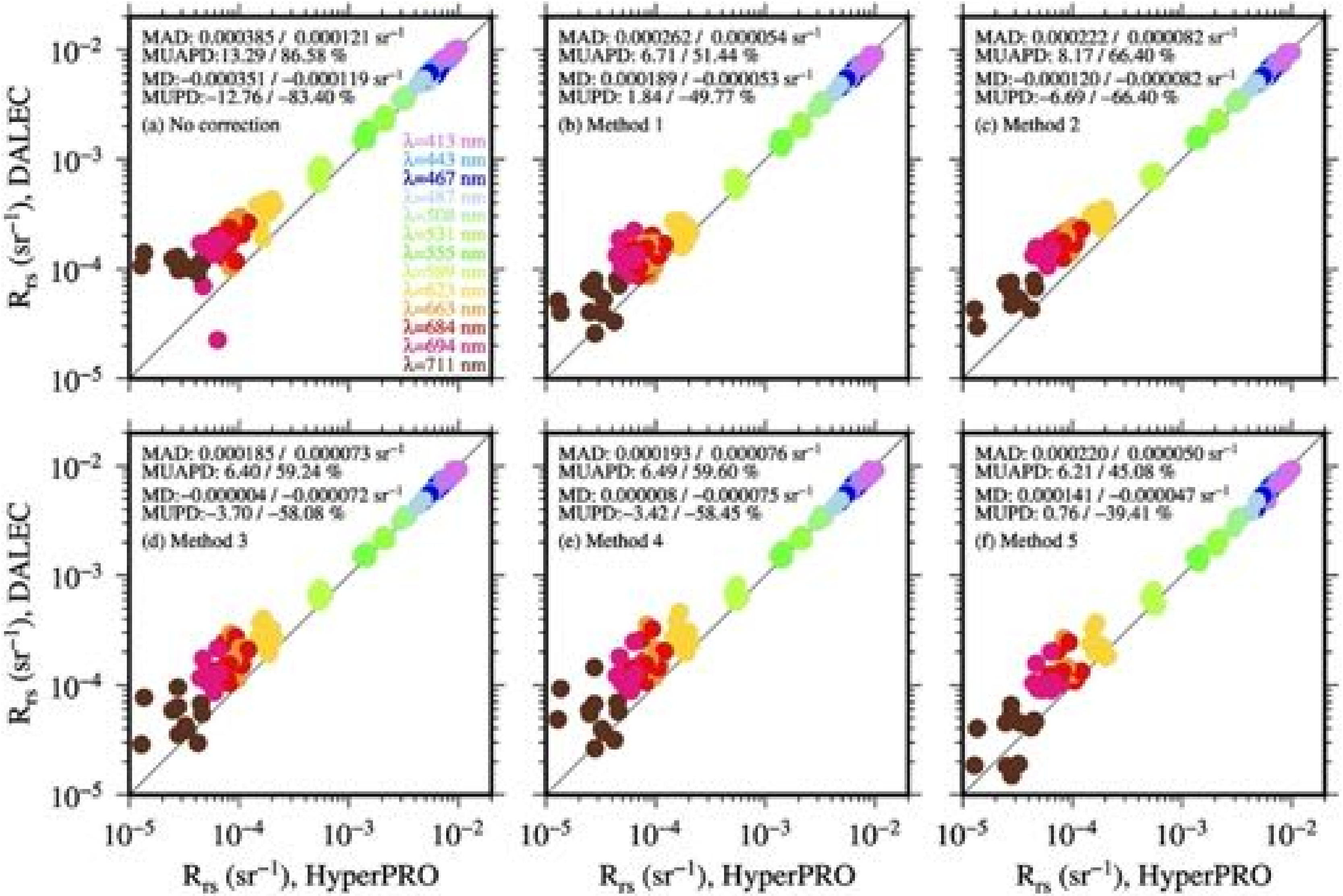


Comparison buoy-Free fall profiling
(Antoine et al., JGR, VOL. 113, C07013, doi:10.1029/2007JC004472)



Comparison of 2 in-water profilers
(Antoine et al., Optics Express, 2021, https://doi.org/10.1364/OE.412022)

Comparing data sets

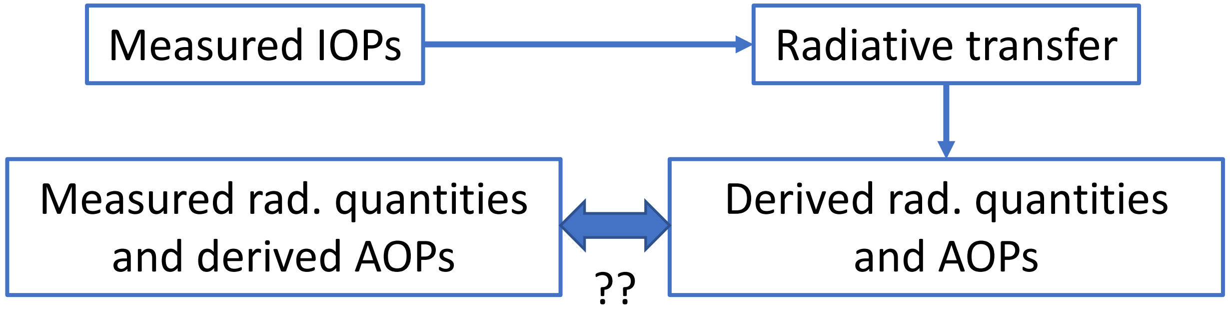


(Antoine et al., Optics Express, 2021, https://doi.org/10.1364/OE.412022)

Optical closure

What is this?

- Derive radiometric quantities and AOPs from radiative transfer using measured IOPs as inputs, and compare to the measured radiometric quantities and AOPs

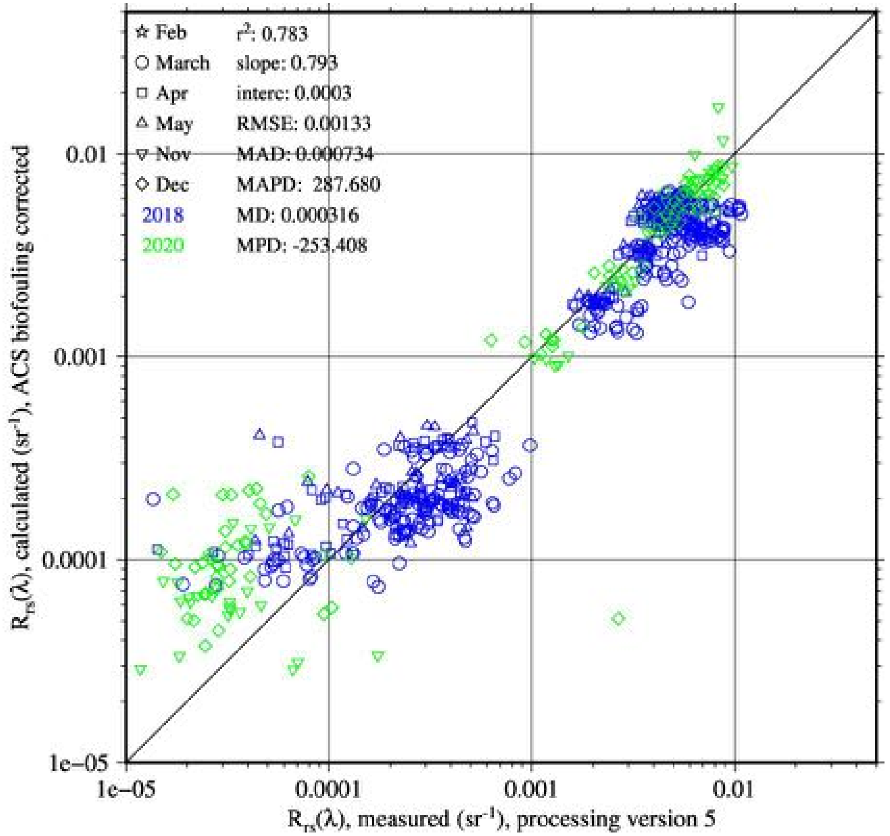


What is required?

- Total absorption, total scattering and the phase function (PF)
- Boundary conditions (sun elev., interface, bottom)

Main question is: do I have the required information to make it relevant?

- The particulate matter PF is generally unknown: the backscattering ratio must be known
- Typically: an AC-S would give you the required absorption and scattering data



An example from a "Thetis profiler", deployed off Rottnest Island, Western Australia

Example of programs addressing the uncertainty issue

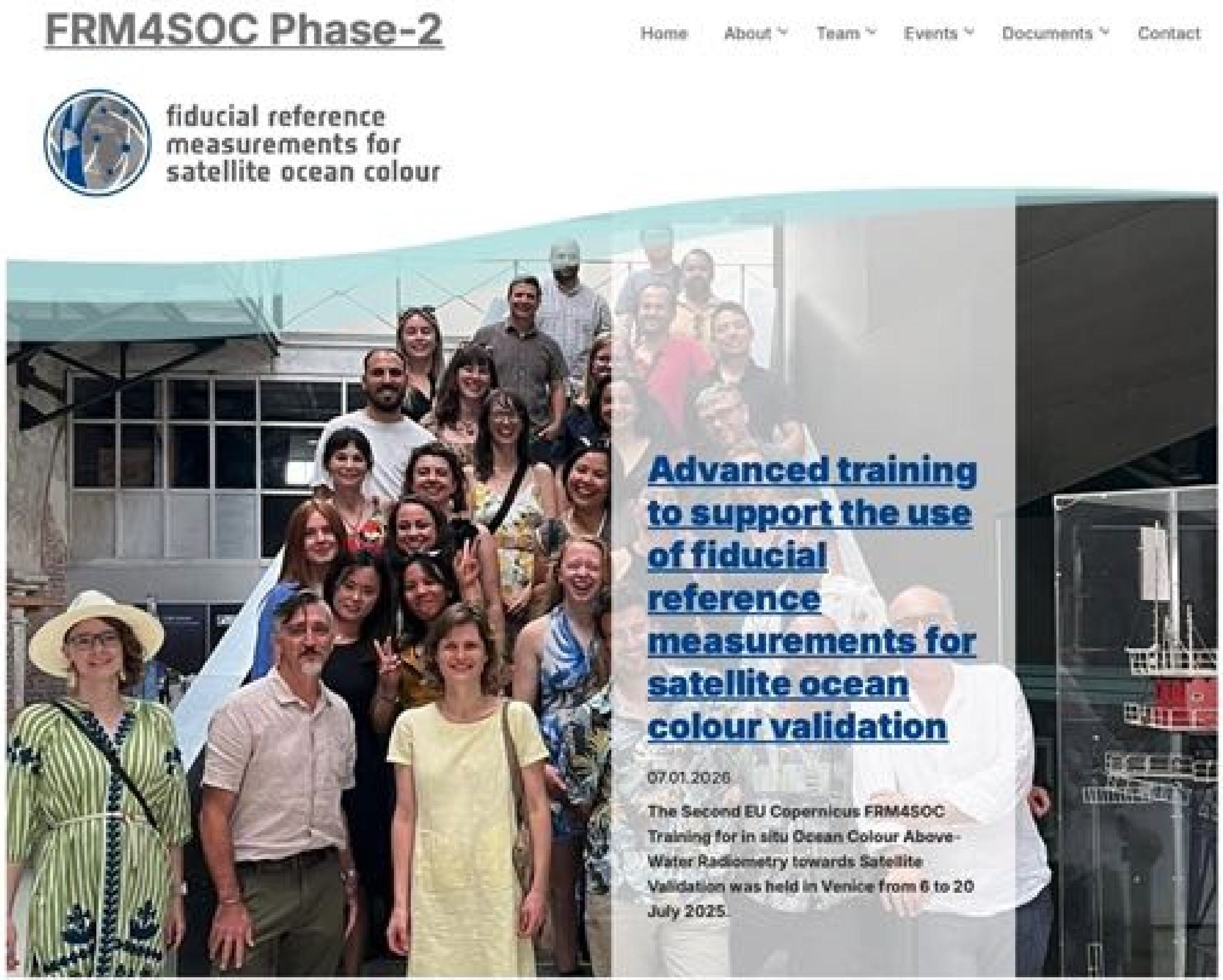
PROGRAMME OF THE EUROPEAN UNION

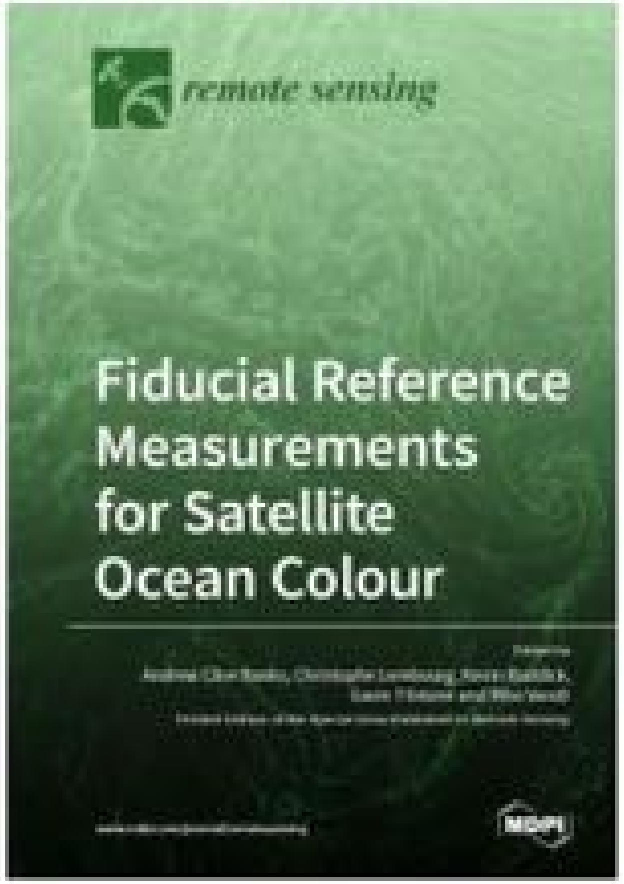
IMPLEMENTED BY EUMETSAT

https://frm4soc.org

https://frm4soc2.eumetsat.int

https://www.mdpi.com/journal/remotesensing/special_issues/2nd_ocean_color_RS



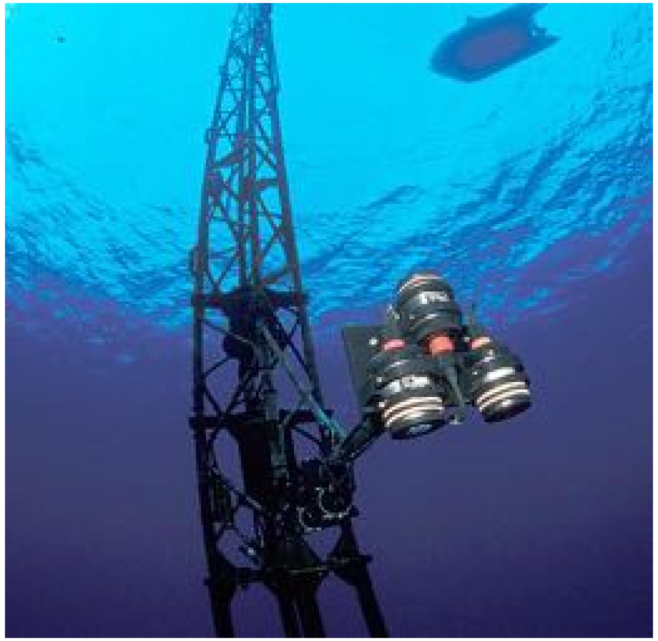
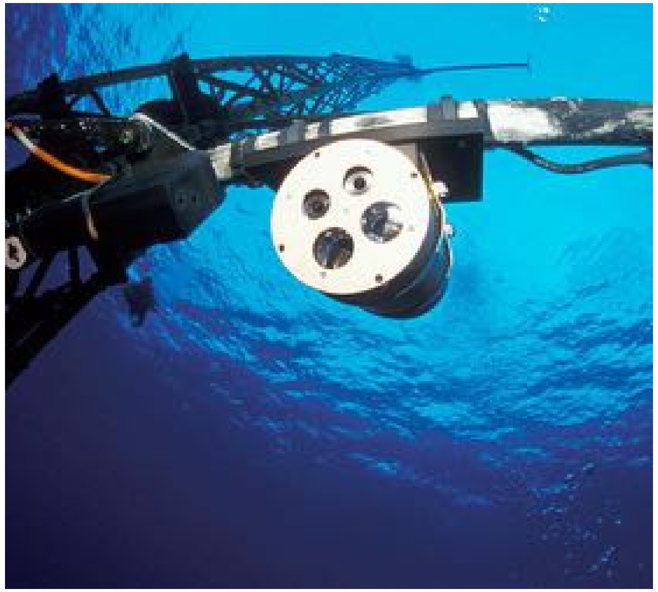


Example of programs addressing the uncertainty issue

https://www.npl.co.uk/earth-observation

https://oceancolor.gsfc.nasa.gov

https://ioccg.org

Thanks for your attention