Radiometry, apparent optical properties, measurements & uncertainties

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IOCCG Summer Lecture Series

* Some slides from M. Twardowski's "Observational Approaches to Ocean Optics" course

My Background:

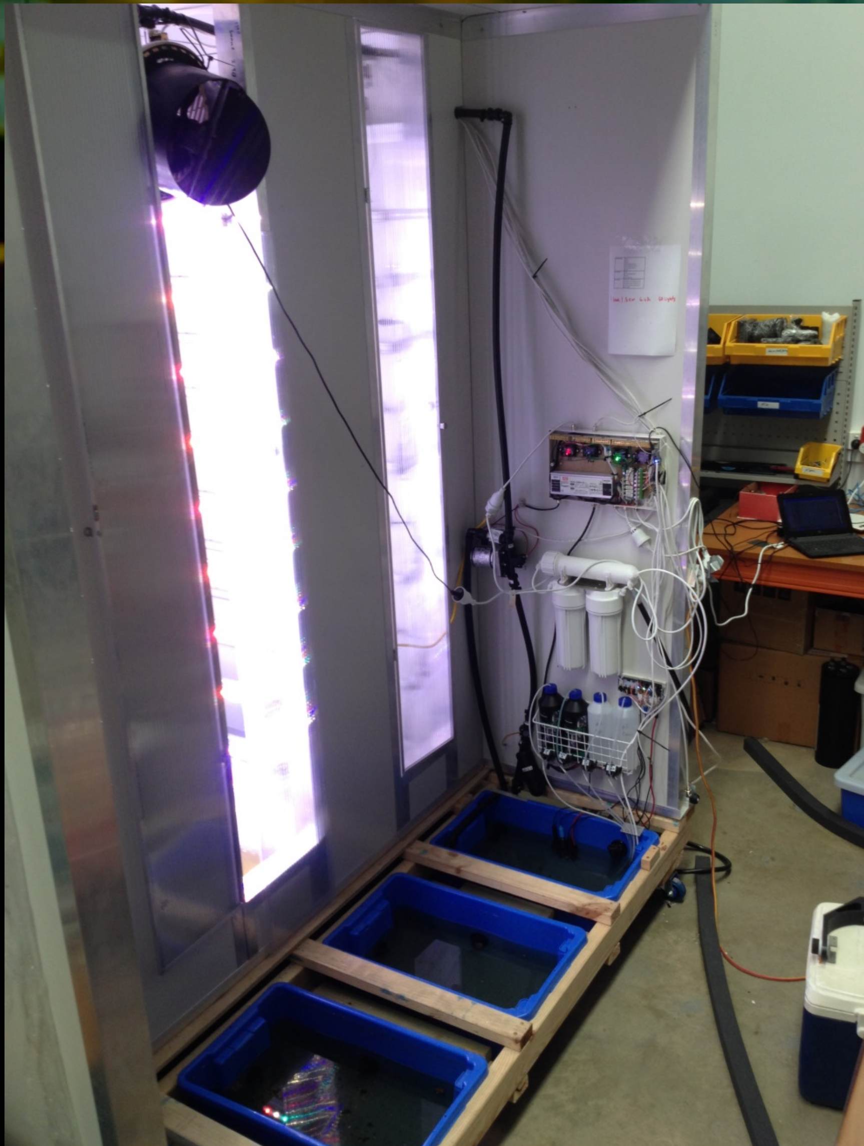
- Doctoral Thesis: “Ocean Colour Remote Sensing of the Great Barrier Reef Waters” started 2004 (Australian Institute of Marine Science)
  - In-situ above water reflectance (developed the DALEC 3 channel radiometer)
  - Coincident IOP (QFT, Hydroscat, benchtop CDOM)
  - Relationships between IOP -> F:Chl-a, TSM, DOC
  - Mie scattering theory (phase functions)
  - Hydrolight simulations R_{rs} -> $b_b/(a+b_b)$
  - MODIS ocean colour algorithm development and matchups
- Company “In-situ Marine Optics” (Australia) started 2007
  - Consultancy for Mining / Oil and Gas Port Expansion industry
    - MODIS TSM algorithm development and image provision
    - In-situ K_{dPAR} vs TSM vs NTU
    - LISST Particle Size distribution
    - Data anlaysis
  - Optical Oceanographic Instrument development
    - www.insitumarineoptics.com
- WETLabs East (Mike Twardowski) started 2008
  - IOPs
  - Volume Scattering Function from the LISST
  - Mie-based PSD inversion kernel
- Curtin Uni. (D. Antoine)
  - lab and in-situ radiometric sensor intercomparisons.
  - operating autonomous moored profiler (WETLabs Thetis) for radiometry and IOPs

Personal

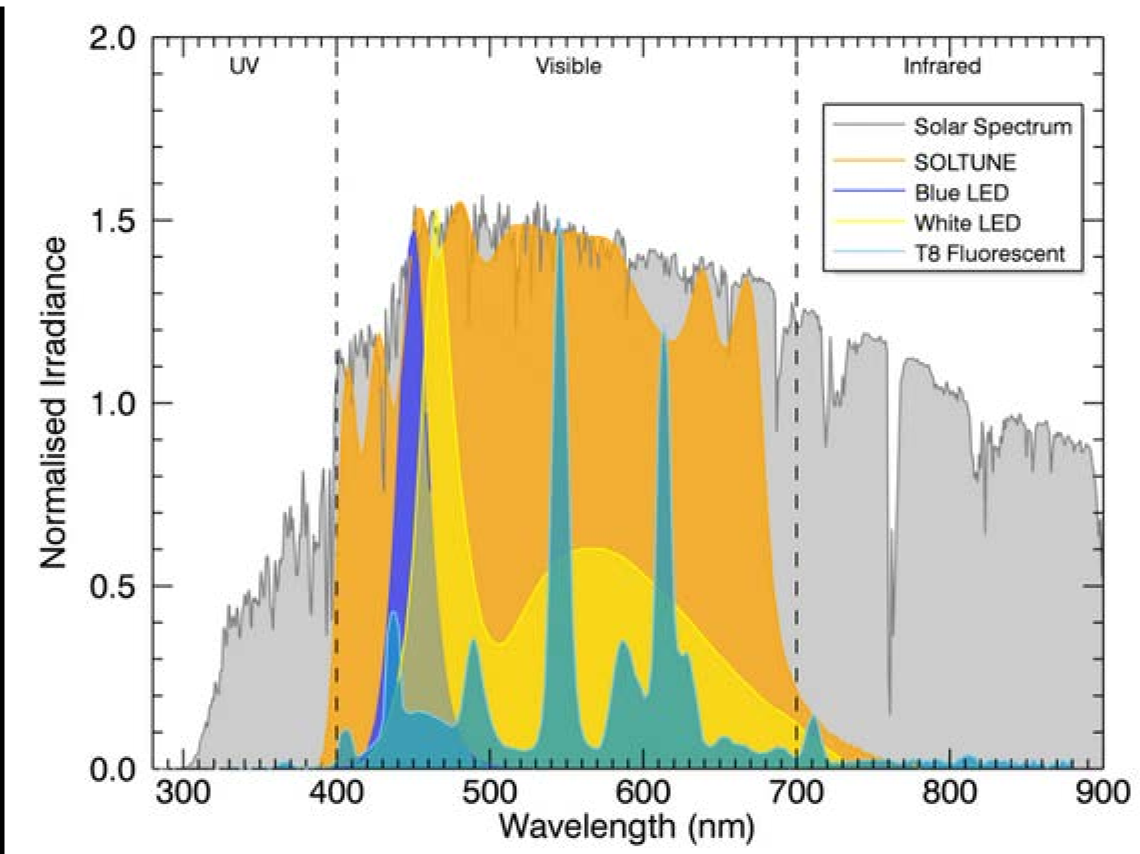
- Long walks on the beach
- Swimming
- Gardening (edibles)
- Beekeeping
- Cooking
- Bass Guitar / Drums
- Camping
- Taking things apart (breaking stuff)
- Trying to fix stuff


Pearl

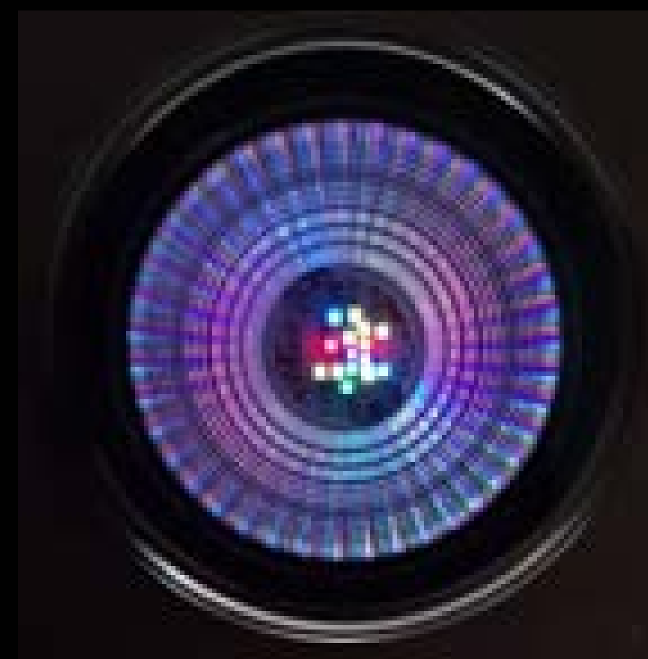

1CJI 930




foodcubed.co



UV
Visible
Infrared
Solar Spectrum
SOLTUNE
Blue LED
White LED
T8 Fluorescent
Normalised Irradiance
0.0
0.5
1.0
1.5
2.0
300
400
500
600
700
800
900
Wavelength (nm)



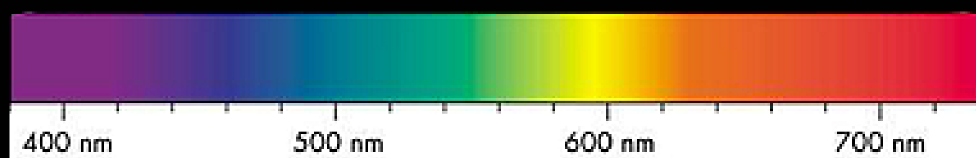
Contents

- Radiometry
  - – Light Detectors
  - – Calibration
  - – Characterisation

- Uncertainties in AOP Methods
    - Diffuse Attenuation
    - Remote Sensing Reflectance

Radiometry

- The measurement of electromagnetic radiation
- Photons – quantised wave packets. $q=hc/\lambda$
- In ocean optics…
  - UV, VIS, NIR wavelengths (200-1000nm)



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

Radiometry

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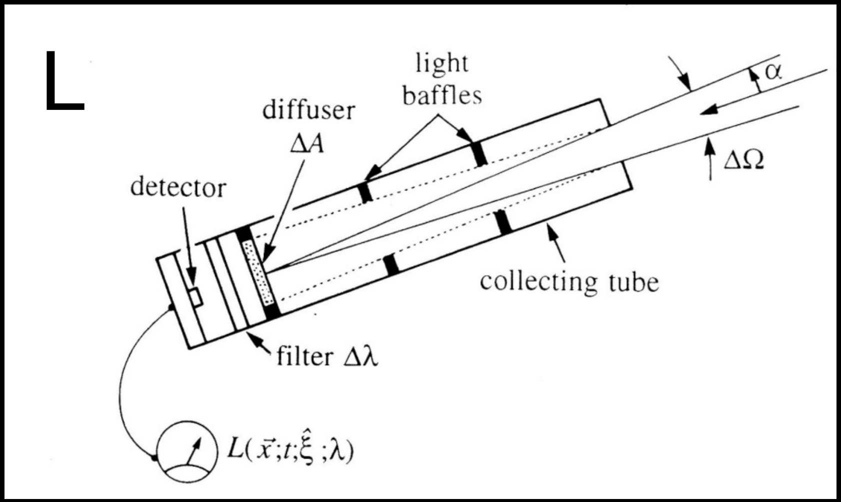

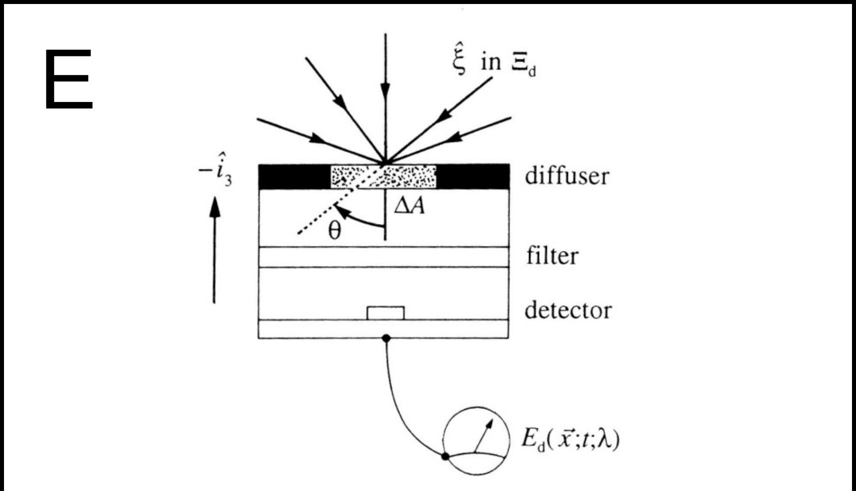

C. Mobley http://www.oceanopticsbook.info

Why Radiometry?

- Spectral radiometric measurements can contain information about the medium and substances within – “hyrosols”
- Non-contact* and Non-destructive** (for the most part)
- Remote Sensing platforms exist that observe oceanic / coastal phenomena over unique time and space scales
  - Satellite imagers (CZCS, SeaWiFS, MODIS etc.)
  - LIDAR
  - AUVs
  - Moored profilers
- Direct quantification of the light field is needed for certain applications
  - productivity studies may need to know Photosynthetically Available Radiation (PAR) at depth
  - Energy budgets (heating etc)
- Fairly easy to measure ***

Radiant Flux

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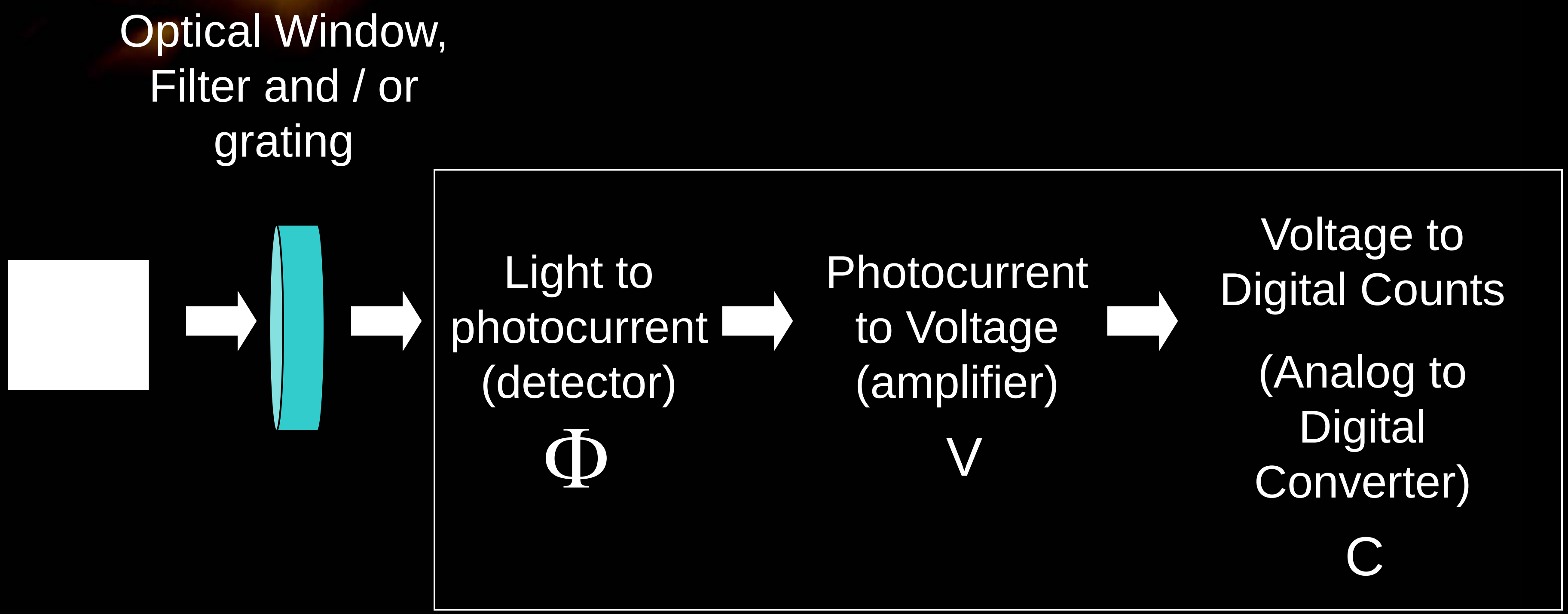
$$\text{Radiant Flux (Power)} = \frac{\text{joules (energy)}}{\text{time}}$$

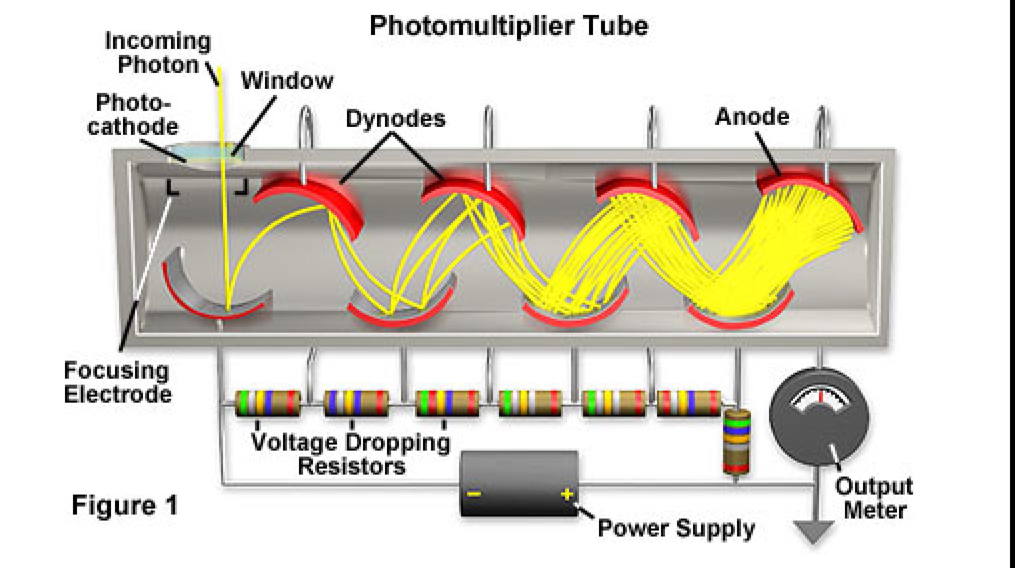
Measured by Quantum (photon) Detectors

Radiant Flux Conversion



Light Detectors: PMT

– 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

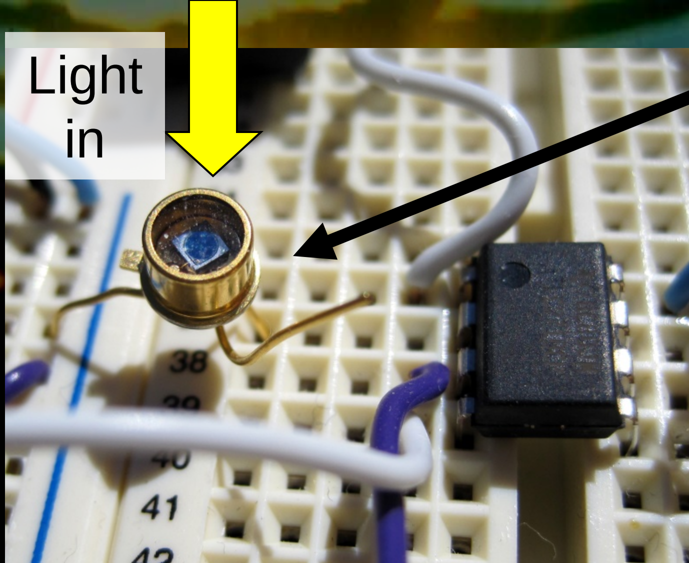


http://learn.hamamatsu.com/articles/photomultipliers.html

Light Detectors: Semiconductor

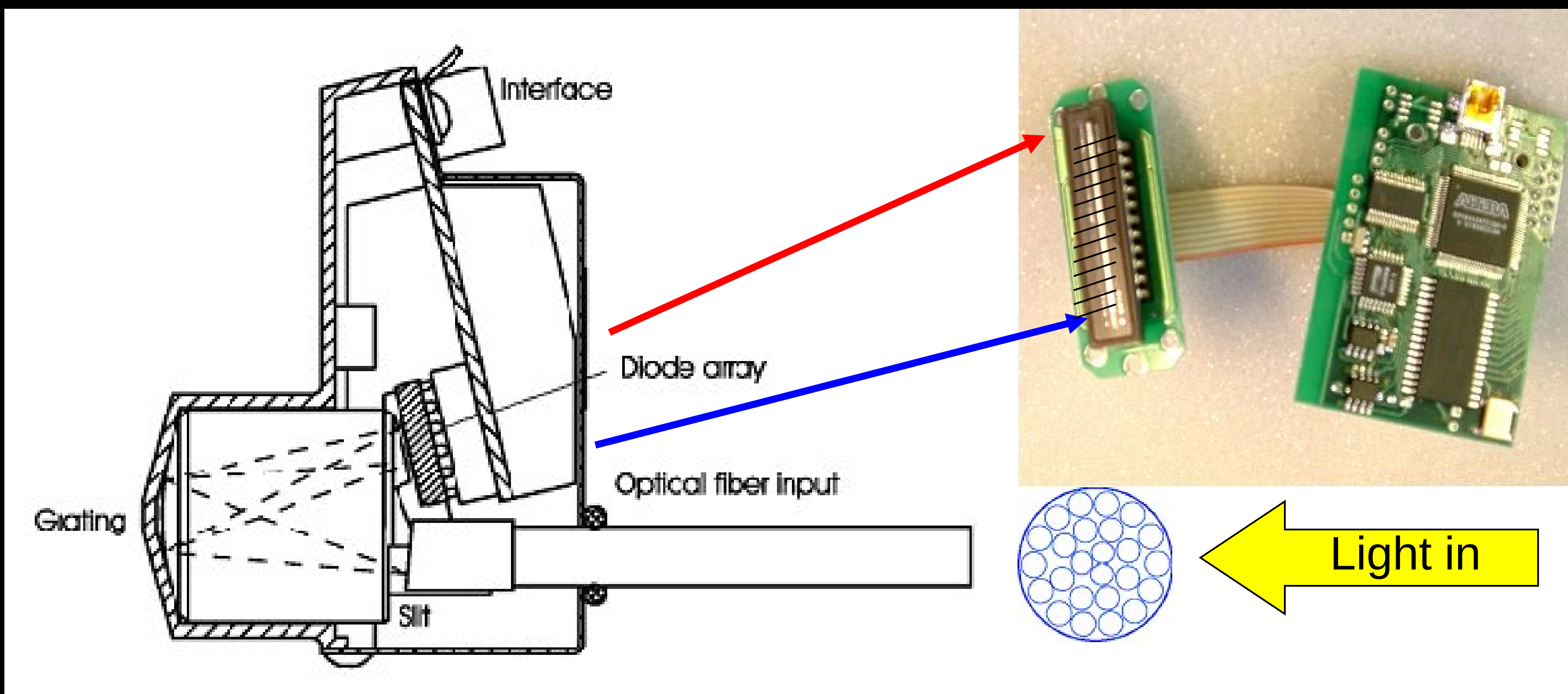
– Semiconductors (i.e. silicon photodiodes used in PAR sensors, OCRs etc.)
  - photon-induced excitation of electrons to the conduction band of the silicon, producing a current

– 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

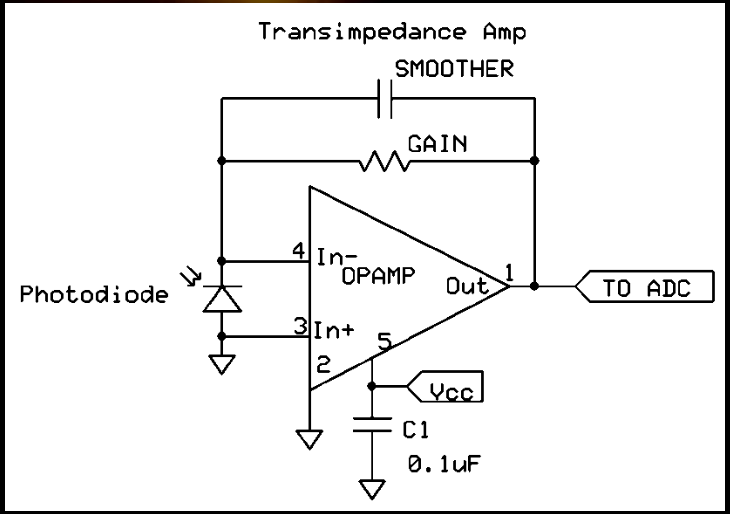


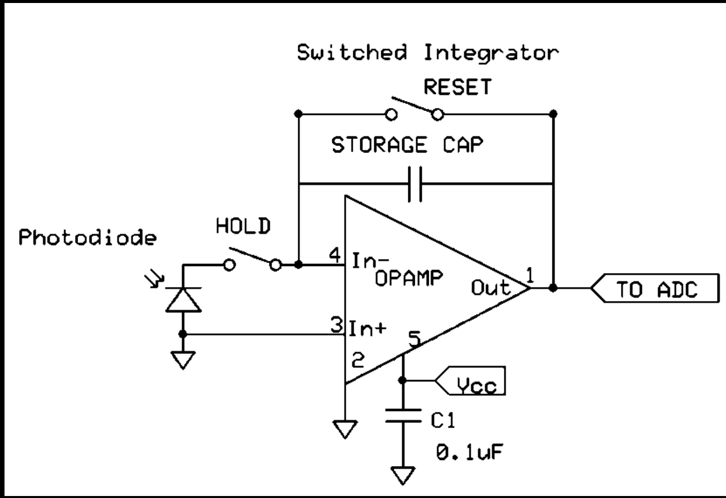
Photodiode with Transimpedance AMP

Diode Array (integrator) with ADC



Current to Voltage Converters

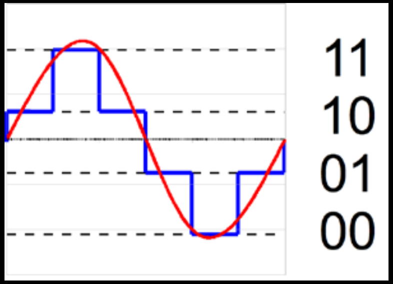




- Transimpedance Amp
  - Sensitivity defined by **gain resistor**
  - Instantaneous voltage output, directly proportional to photocurrent
  - Feedback capacitor acts as temporal “smoother” filter
  - Common approach used in individual photodiode-based sensors i.e. PAR and multispectral where signal is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



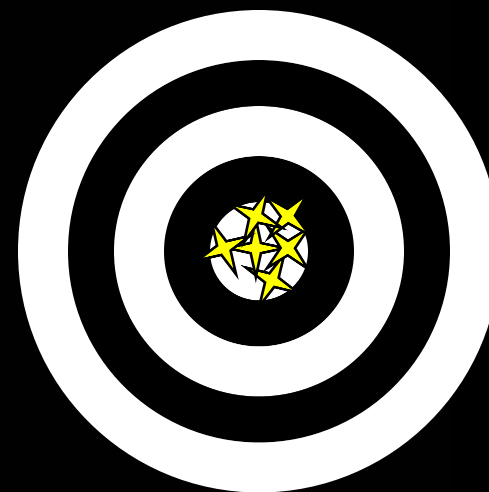
- There’s many different (~15) types of ADC architecture.
- ADC Resolution defined as the number of digital numbers used to represent the converted analog photo current
  - 2 bit resolution = 2^2 = 4 Counts (as shown above)
  - 10 bit resolution = 2^{10} = 1024 Counts
  - 16 bit resolution = 2^{16} = 65536 Counts
- ADC resolution doesn’t necessarily equate to measurement resolution, might be digitizing noise.

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

The quest for truth (bullseye)

High precision,
Low accuracy,

High precision,
High accuracy,



High accuracy,
Low precision,
High uncertainty

Low accuracy,
Low precision,
High uncertainty

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:

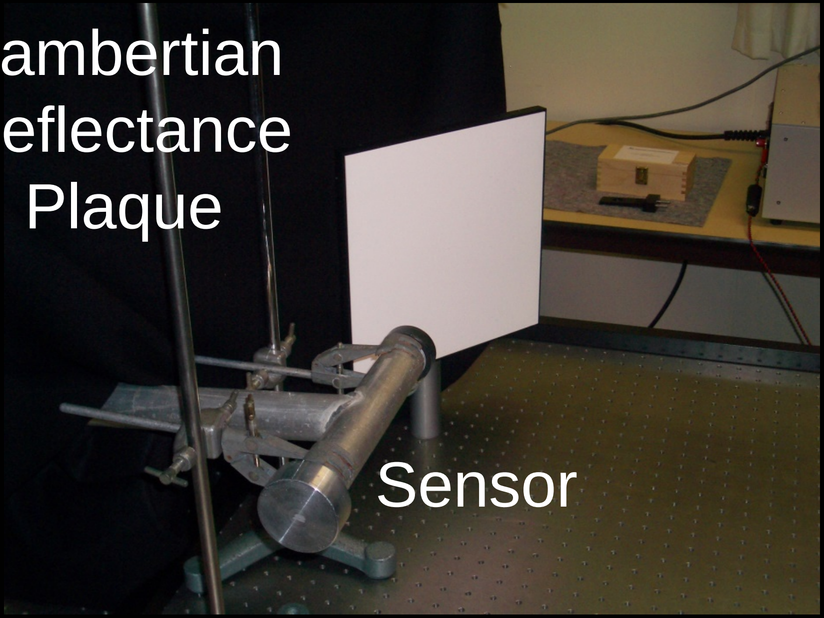
Instrument Specifications, Characterization and Calibration

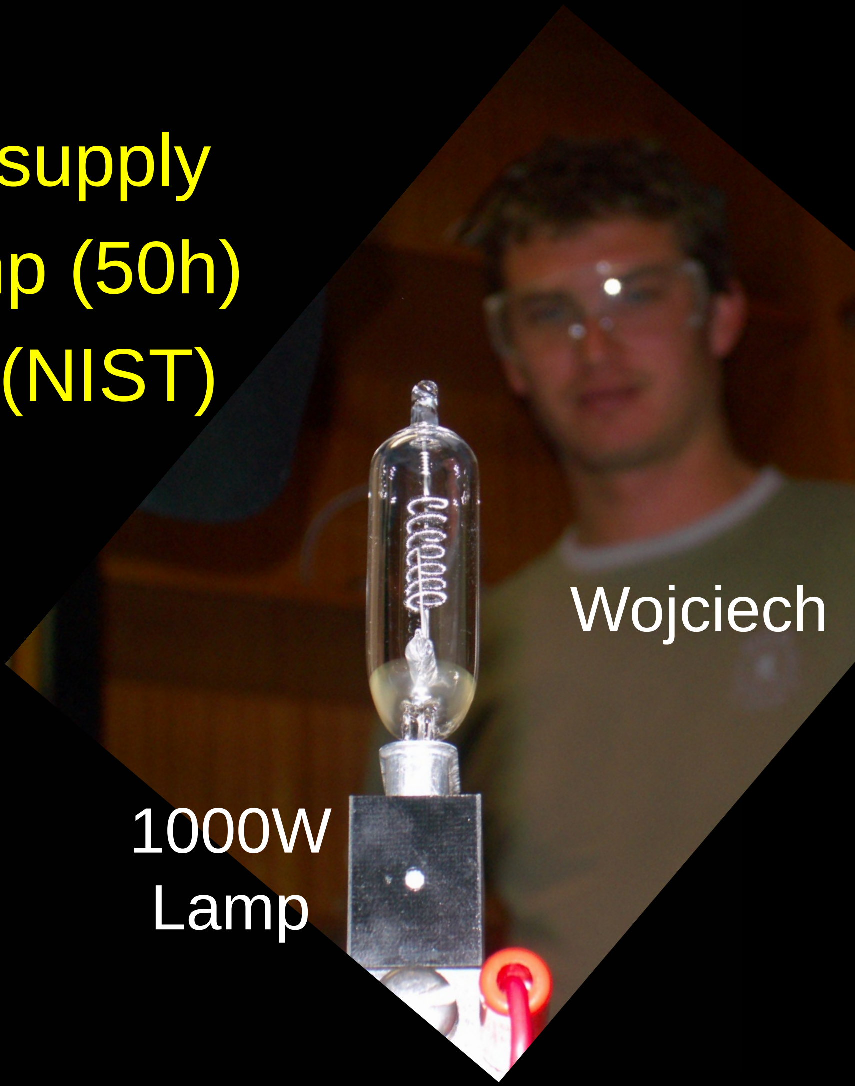
NASA/TM-2003-21621/Rev-Vol II

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.

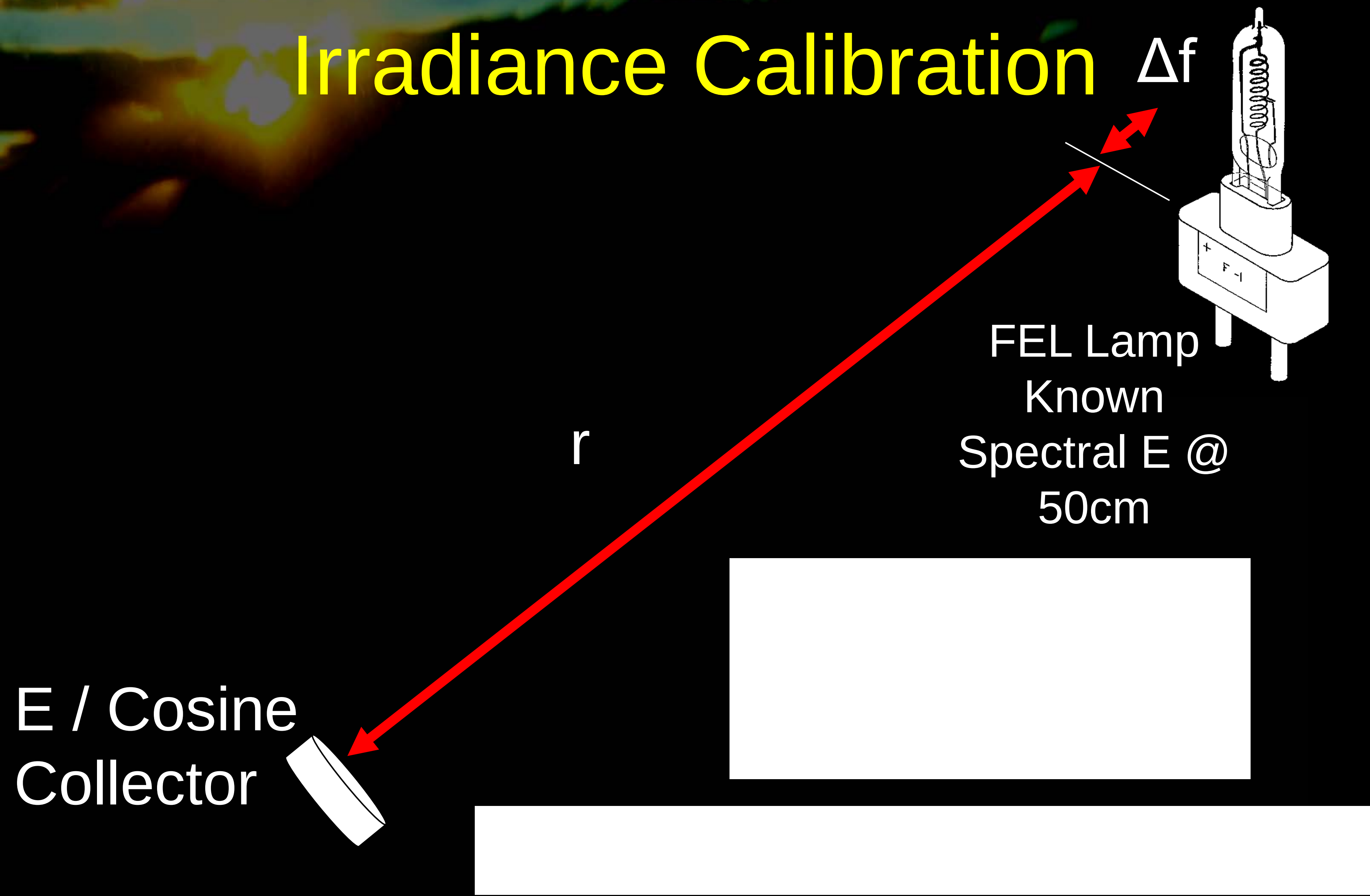
Radiometric Calibration

- Need (at minimum)
  - a stable calibrated power supply
  - a NIST-traceable FEL lamp (50h)
  - Lambertian reflector for L (NIST)

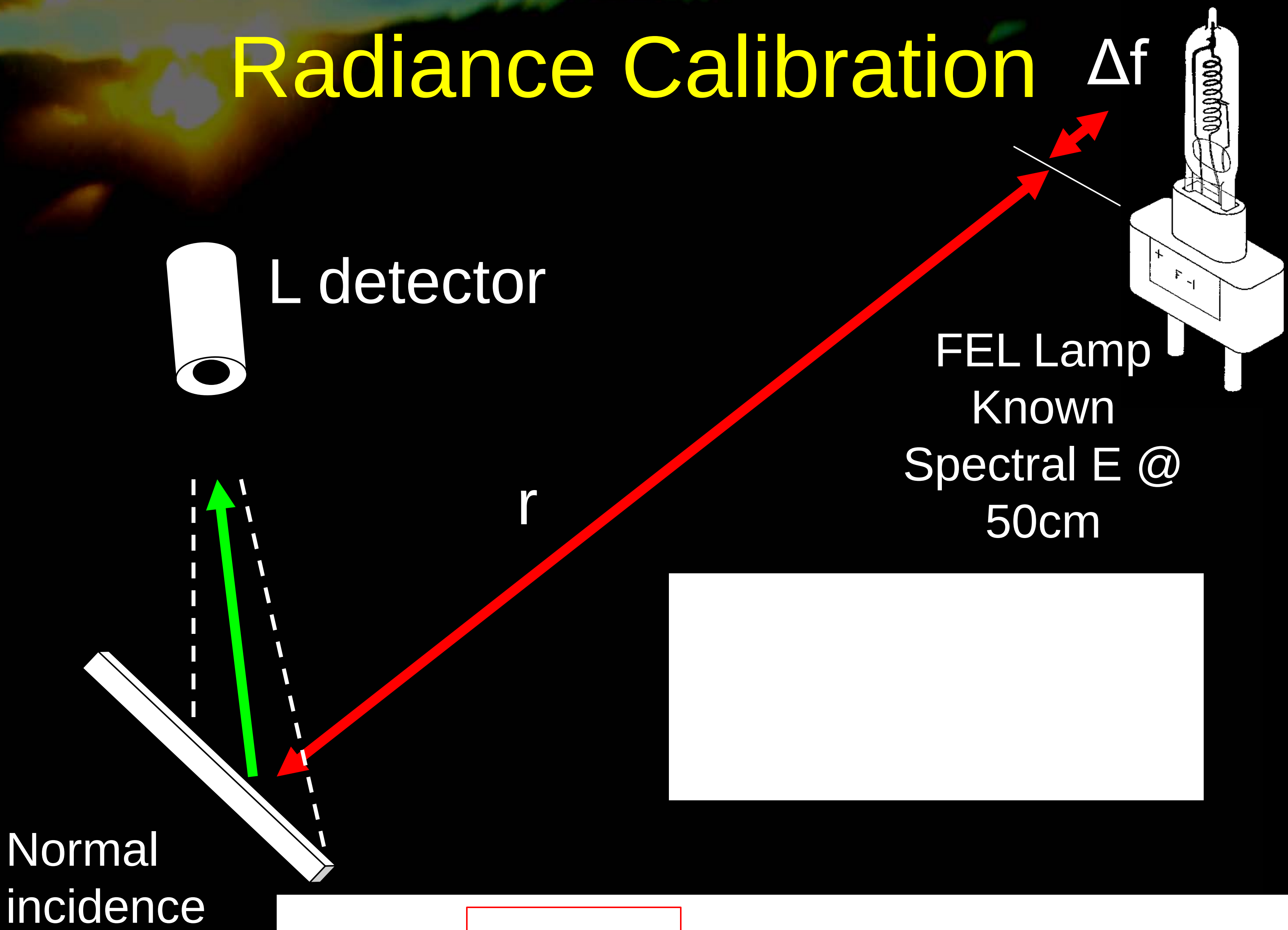


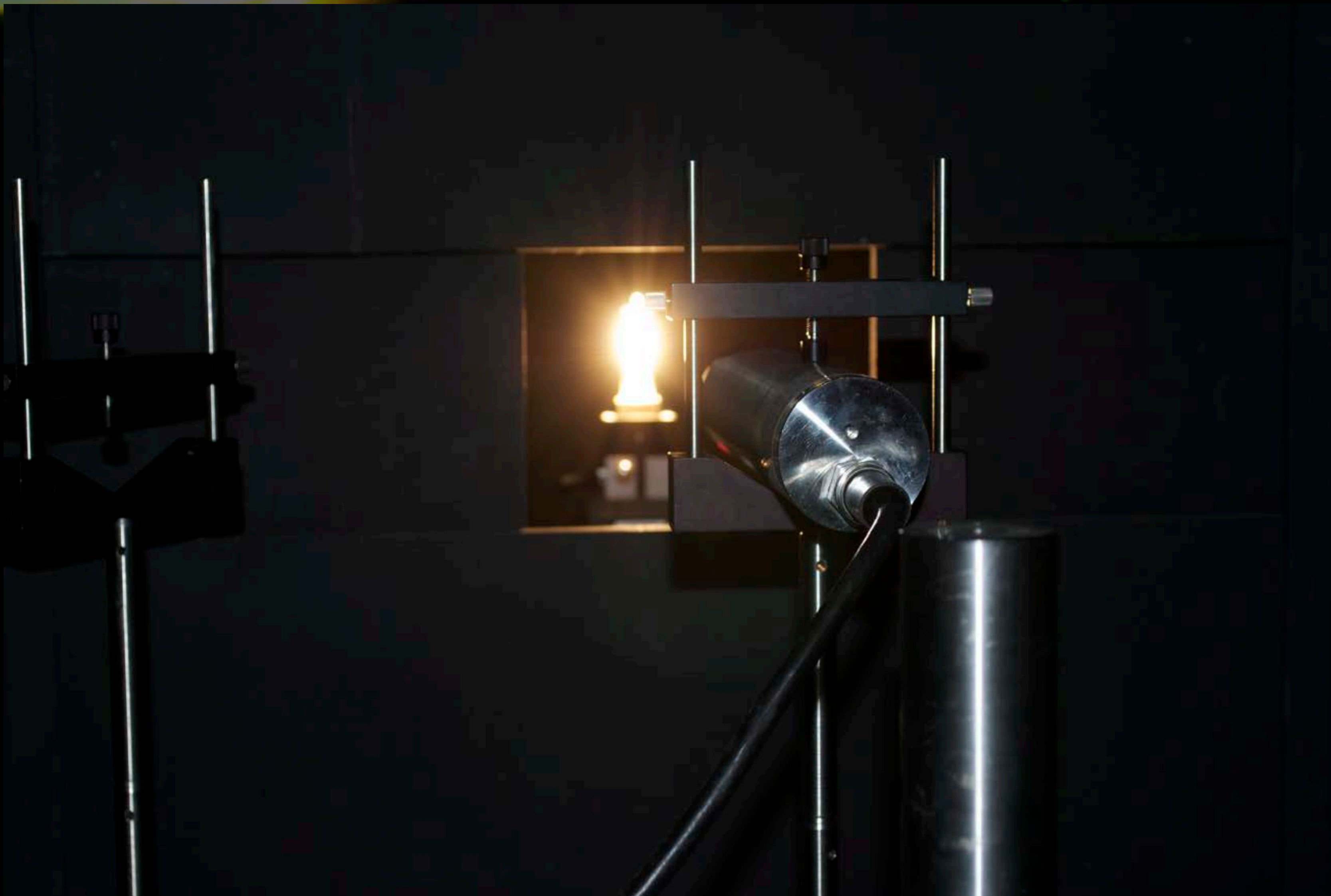


Irradiance Calibration



Radiance Calibration

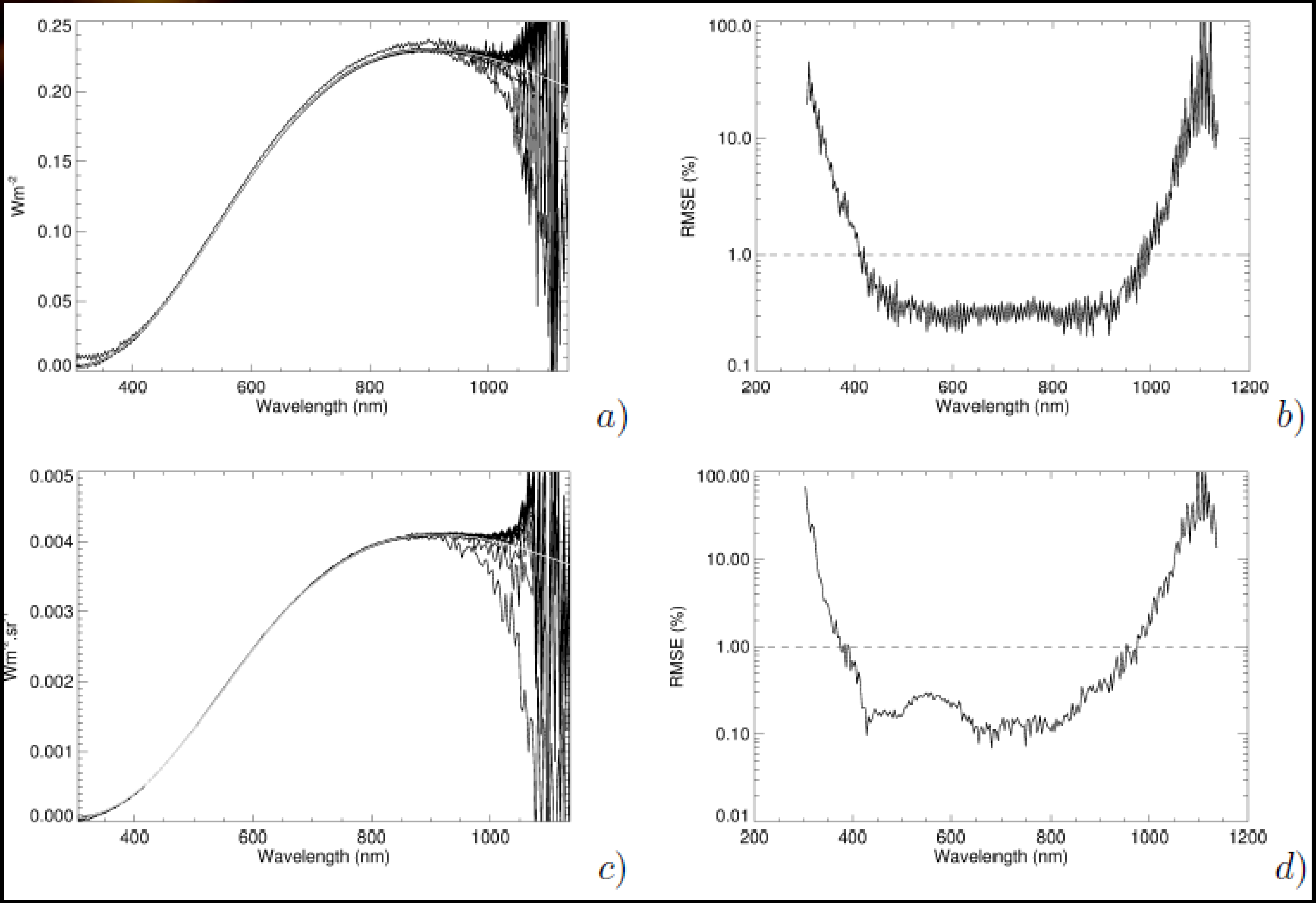




Calibration Uncertainty

- 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
- Delta-f. (distance between the filament and lamp surface) Which part of the filament?
- Spectralon Plaque Reflectivity / Cleanliness
- Power supply accuracy is important (8A)
  - Buy an 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

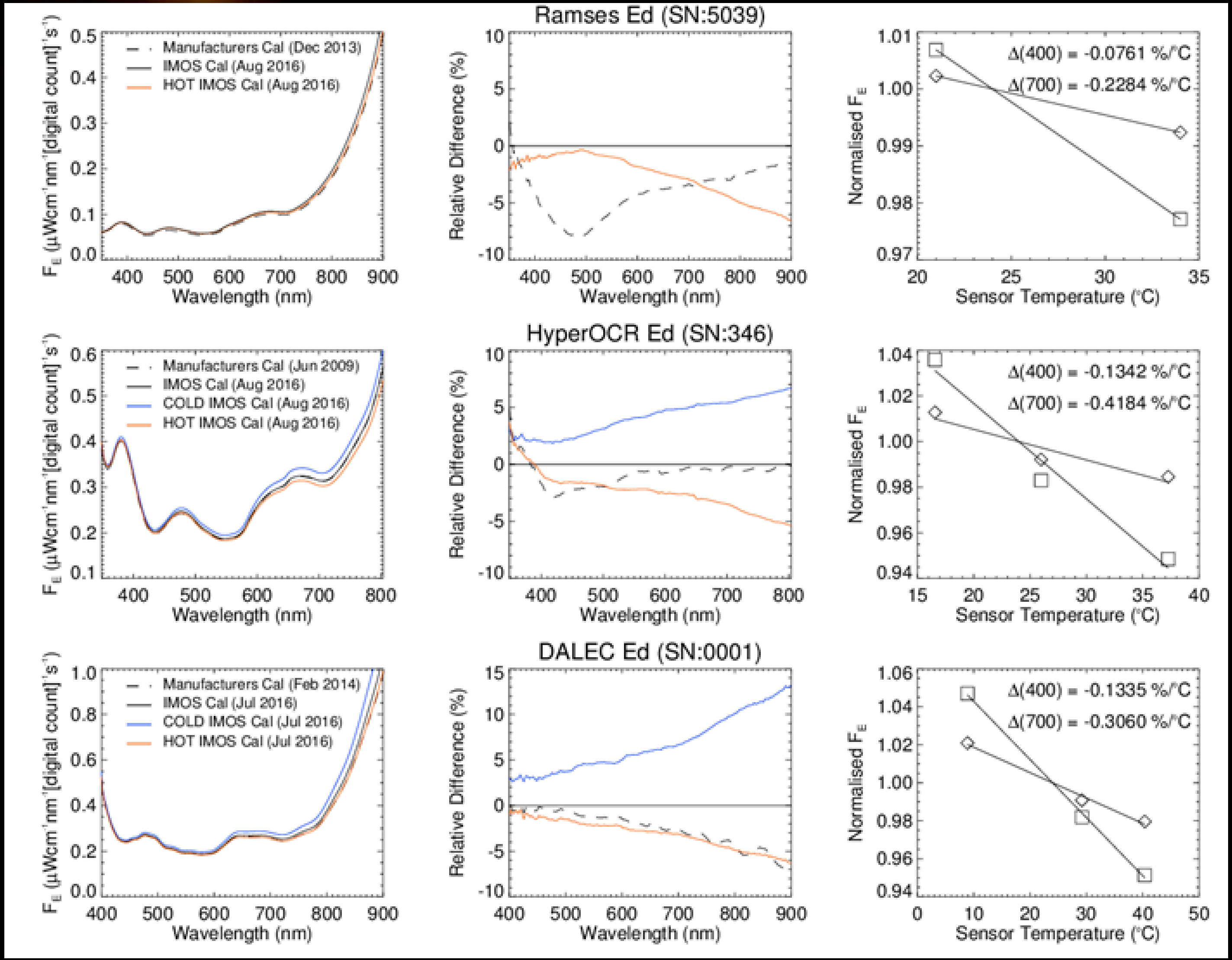
Lamp / Plaque Reproducibility



Radiometric Calibration

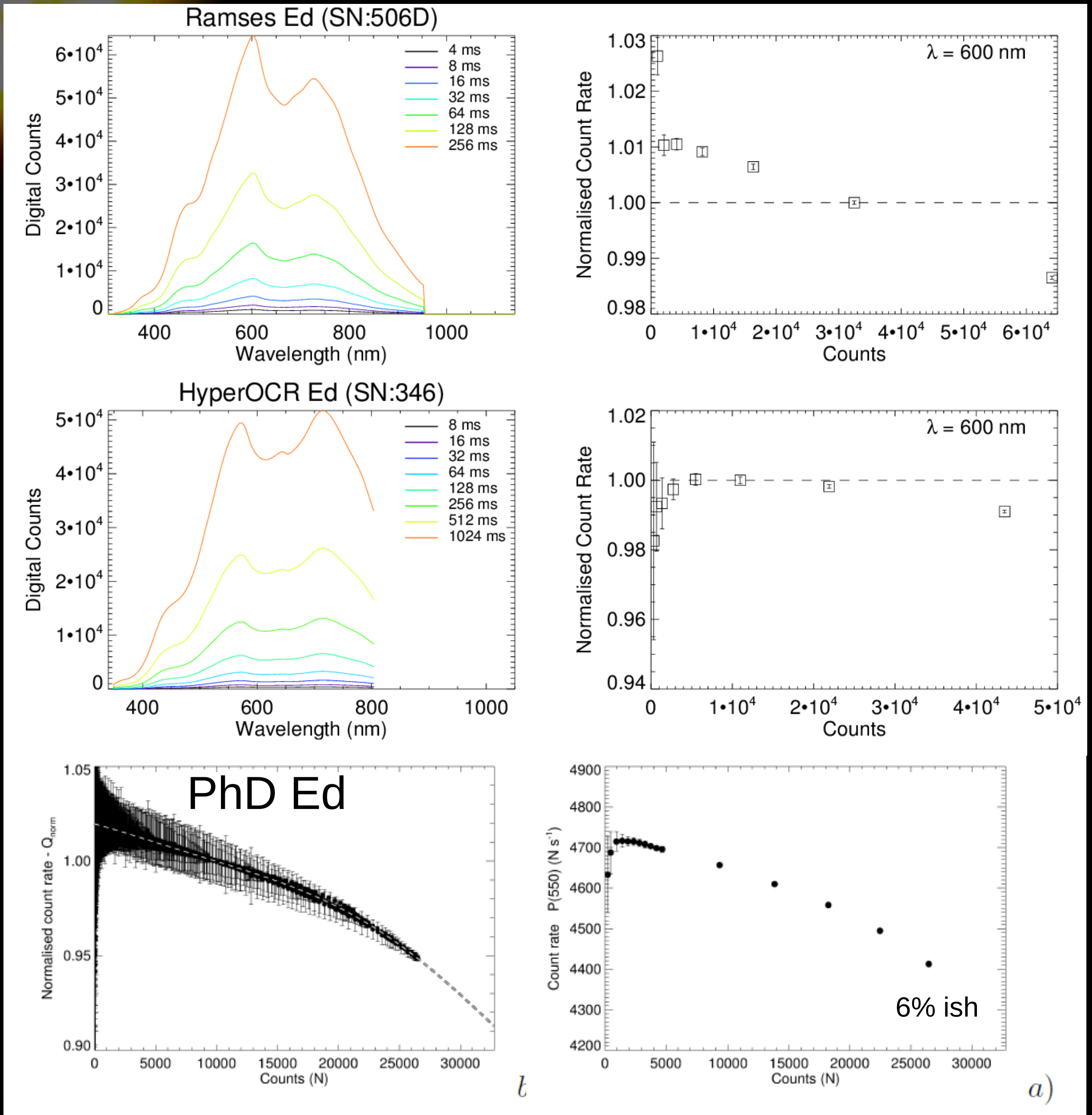
- The transfer of the NIST radiometric calibration standards for ***multispectral*** devices is usually good to 2-3% (Sirrex)
- Recent Findings:
  - Temperature effects of ***hyperspectral*** instruments are considerable, thus a calibration performed at one temperature by the “factory” or lab may be less applicable to a field observation at a different temperature!
  - Ideally, we want to perform calibrations at a few different temperatures to assess the temperature dependency of the radiometer.

Temperature Dependency in Hyperspectral Radiometers

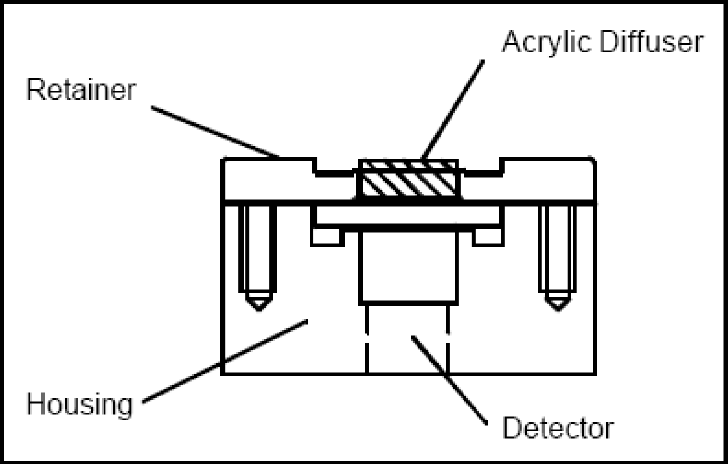


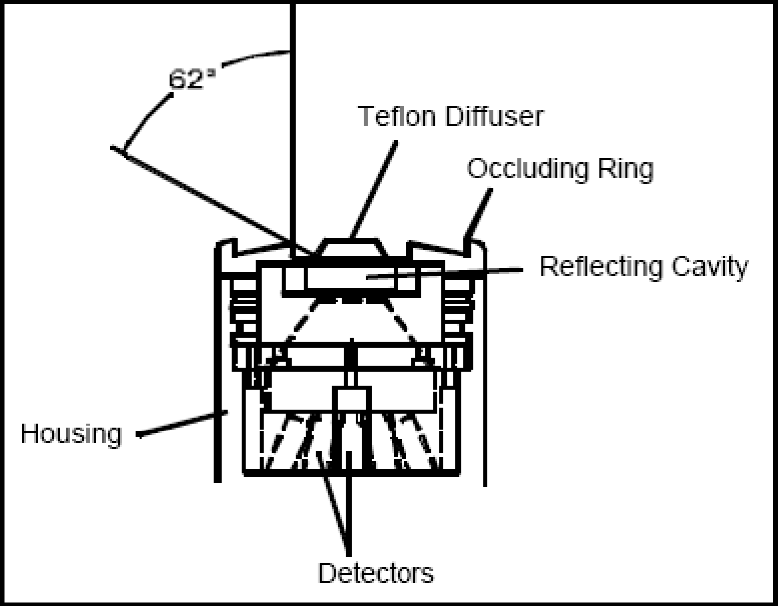
Also see, Zibordi et. al. 2017 jtech

Integration Time Dependency



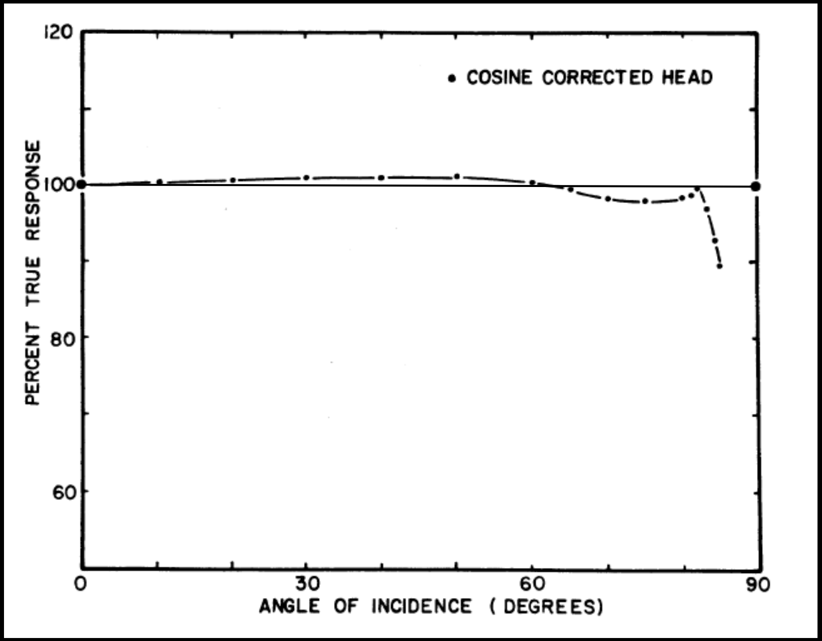
Cosine Response



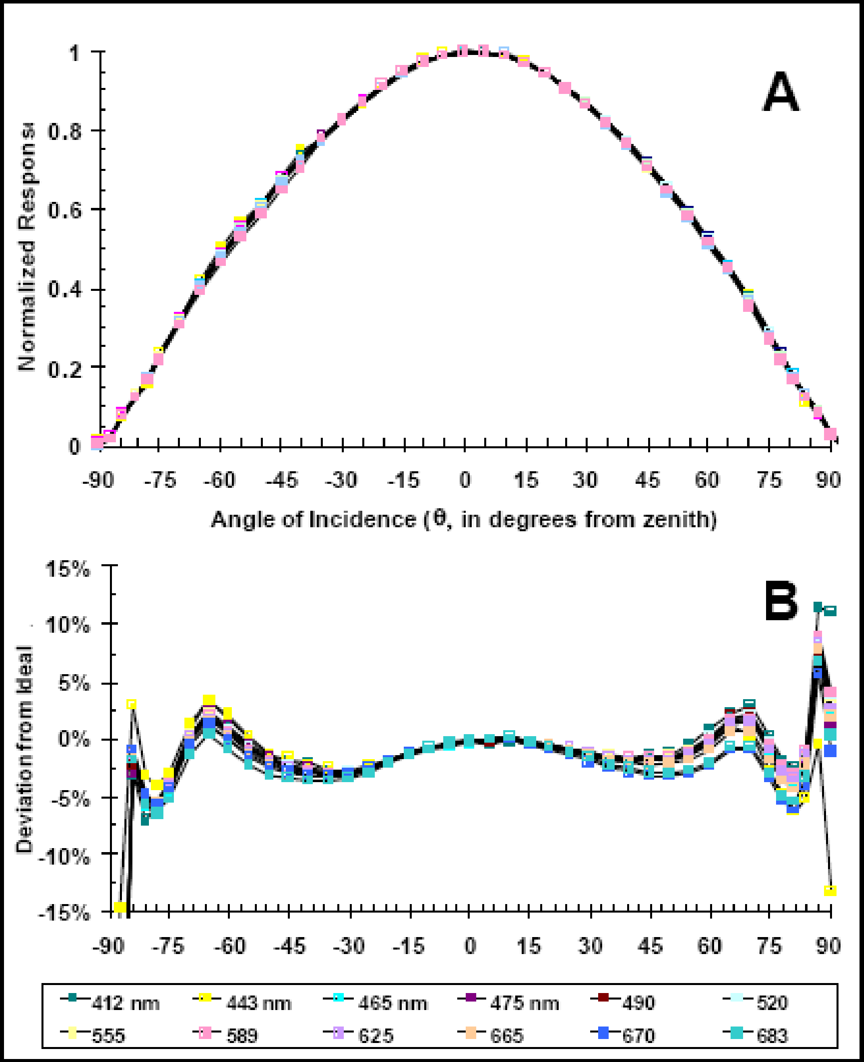


Morrow et al. 2000

Cosine Response



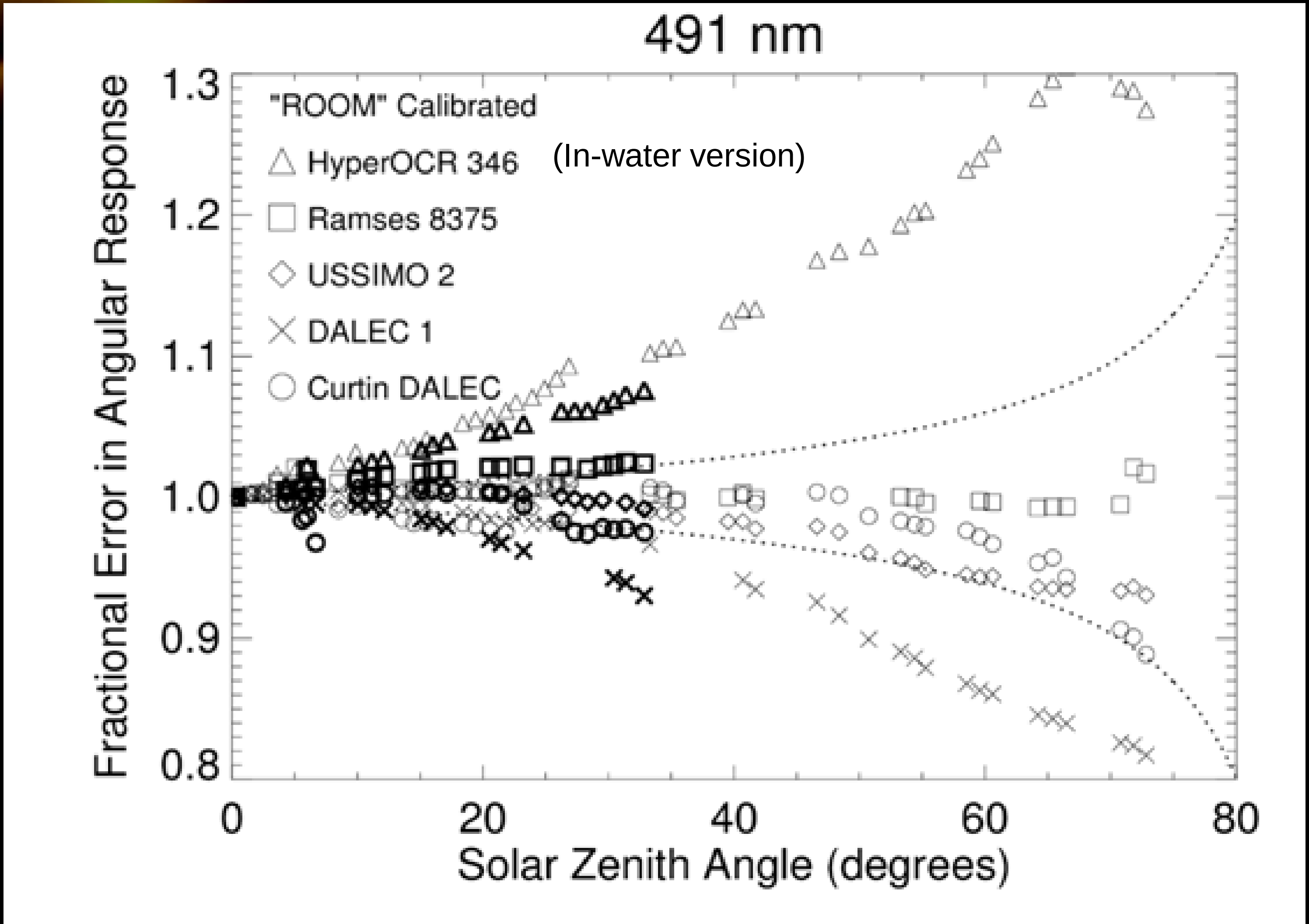
manufacturer’s web page



Morrow et al. 2000

Field Cosine Response

Field Cosine Response



Instrumental uncertainty

- NOISE
  - Thermal noise from silicon detector / resistive elements
  - RF pickup from photodiode and other circuit traces
  - Amplifier power supply and ADC Voltage reference noise
  - Integrator switch time jitter (digitally sourced signal)

Average your data (where appropriate)

- Bias /Drift (with temperature) < 0.5% per degree for hyperspectral devices!
  - Transimpendance Resistance (Gain)?
  - Silicon conduction band / sensitivity (in the red)
  - Amplifier 'DC offset' voltage
  - Integrator capacitance?
  - Integrator switch rise / fall times?
  - ADC nonlinearity a function of temperature?

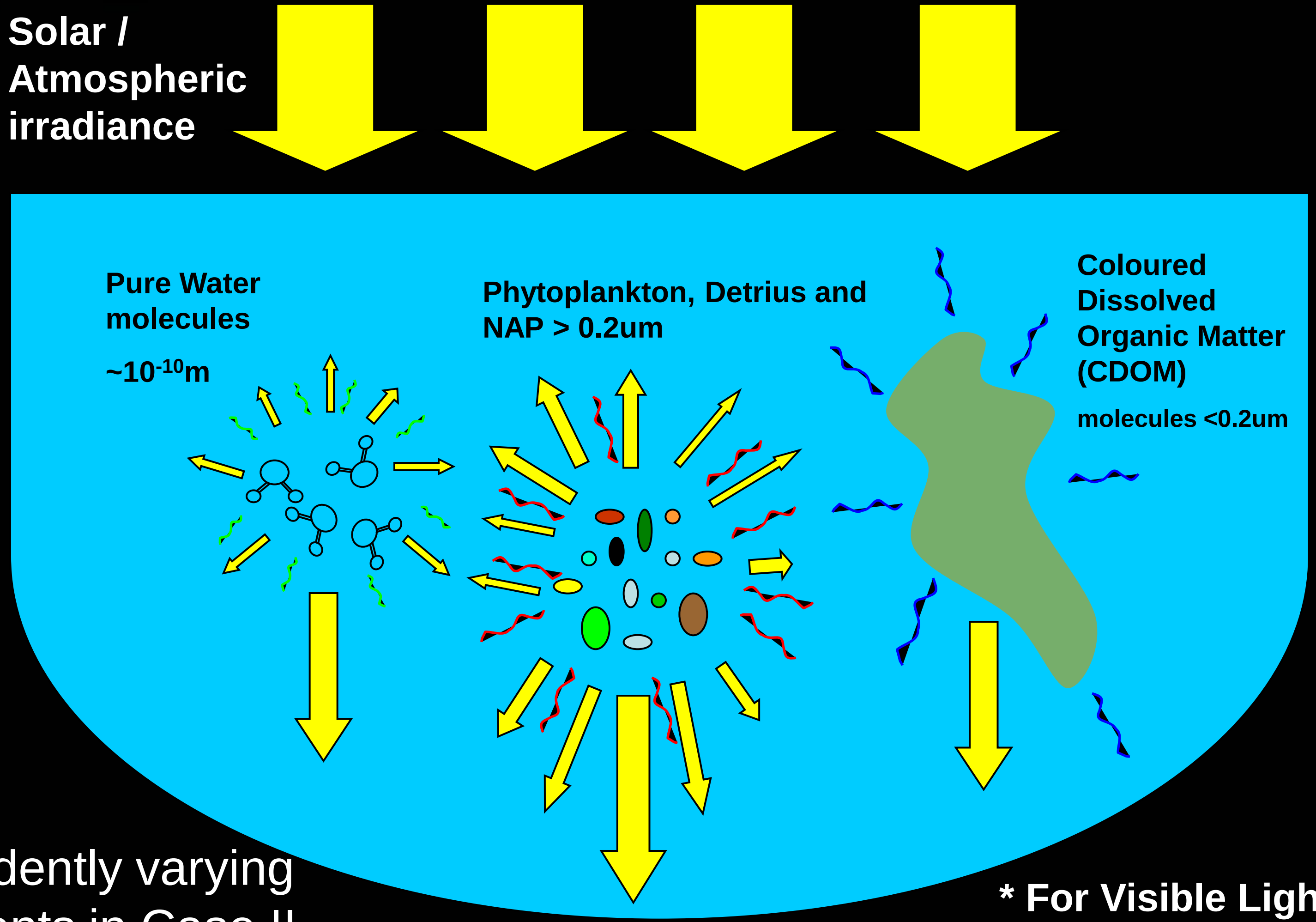
Characterise and correct this. Cal at 3 different temperatures

- Other Bias
  - Dark Offsets (offset voltage and rectified AC noise)
    - Characterise your instrument's 'dark' response in the field and subtract these.
    - Process your data yourself or trust manufacturer's 'black box' processing code.
  - Integration time non-linearity
    - We can model / fix this, but it's typically not done by manufacturers. Fixed int times?
  - Optical filters degrade in time (temperature, light exposure)
  - Optical windows may become fouled or scratched in time
  - Planar Irradiance Cosine Response
    - Consider evaluating this yourself or add larger uncertainties for larger SZA
  - Stray light
    - non-perfect diffraction grating in diode array spectrometers (-1 to 4% errors in Rrs – Talone et. al. 2016)
    - Out of band filter response in the NIR

Please don't be discouraged

- 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"

Optically Active Constituents



Independently varying constituents in Case II

*** For Visible Light ~ 400nm - 750nm**

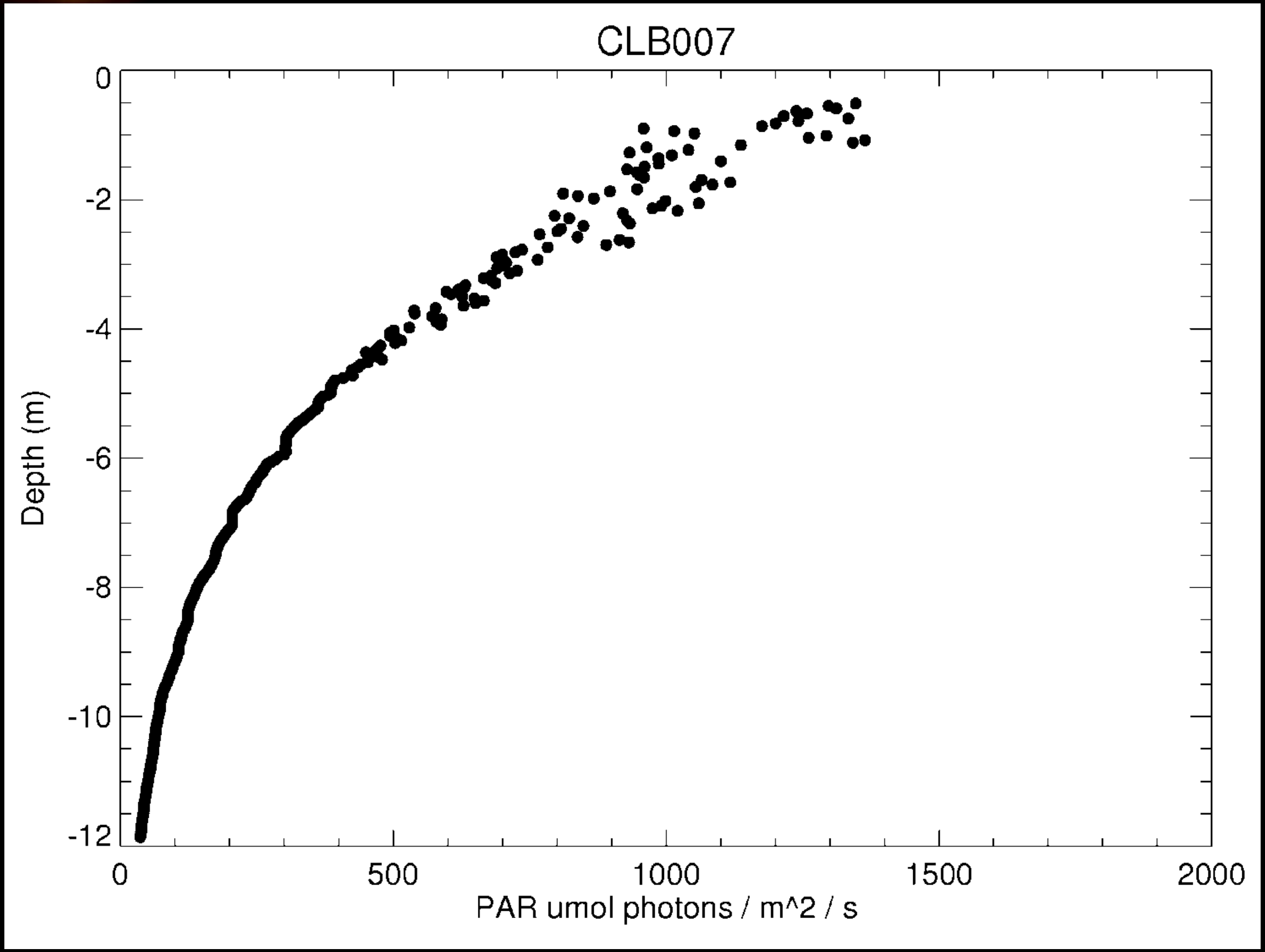
Apparent Optical Properties

- Derived from radiometric measurements using L or E (or both)
  – ratios (reflectance or mean cosines)
  – rates of change (diffuse / radiance attenuation coefficients)
- AOPS are dependent on surrounding light field as well as the substance
  – Solar angle
  – How ‘diffuse’ the surrounding is
- They are related to the IOPS of the substance(s) being observed, but AOPS are easier to measure

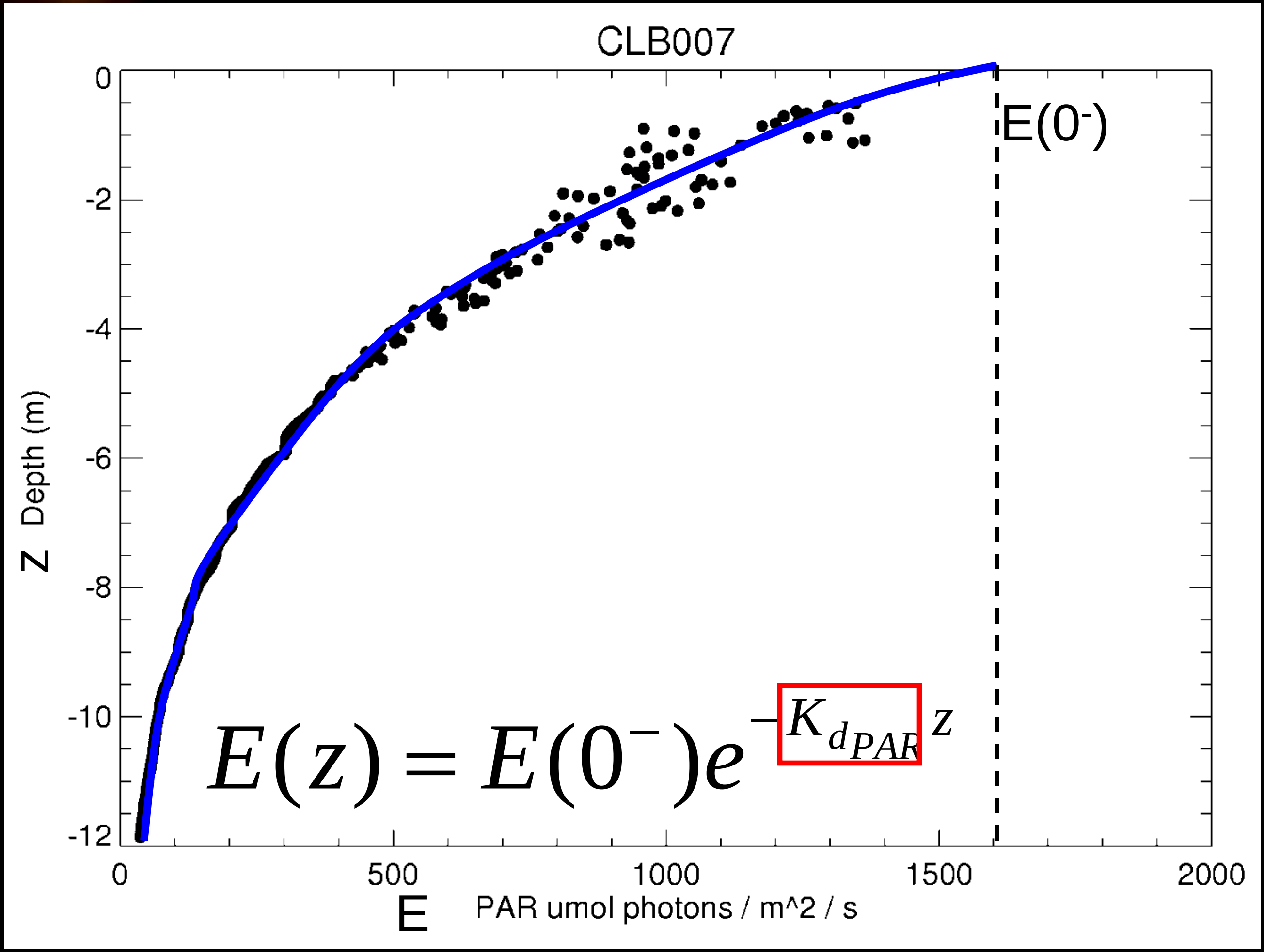
Practical Examples

- PAR light at different depths.
- How spectral irradiance at different depths varies with TSM (TSS).
- Measuring above water R_{rs}

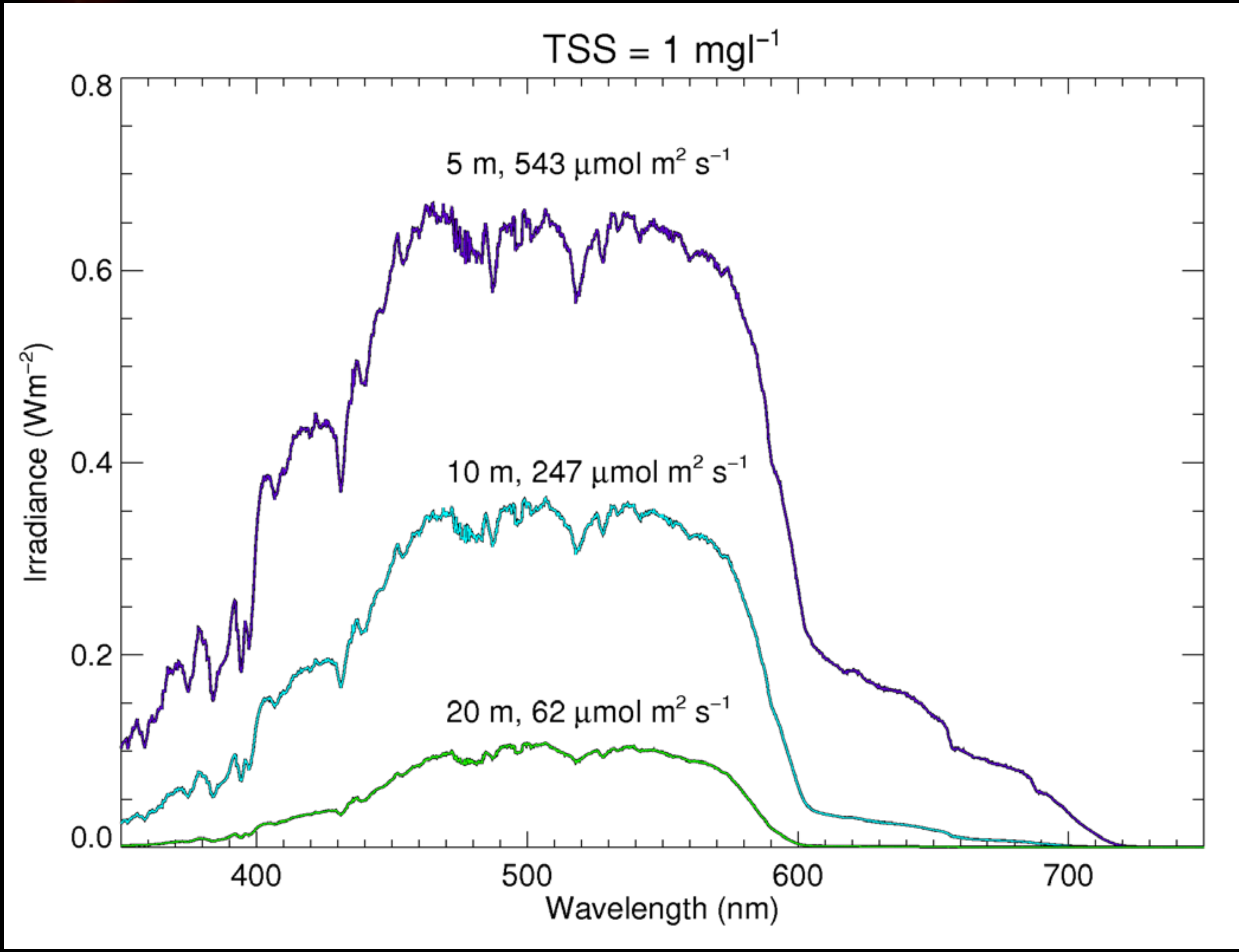
Example: PAR Irradiance Profile



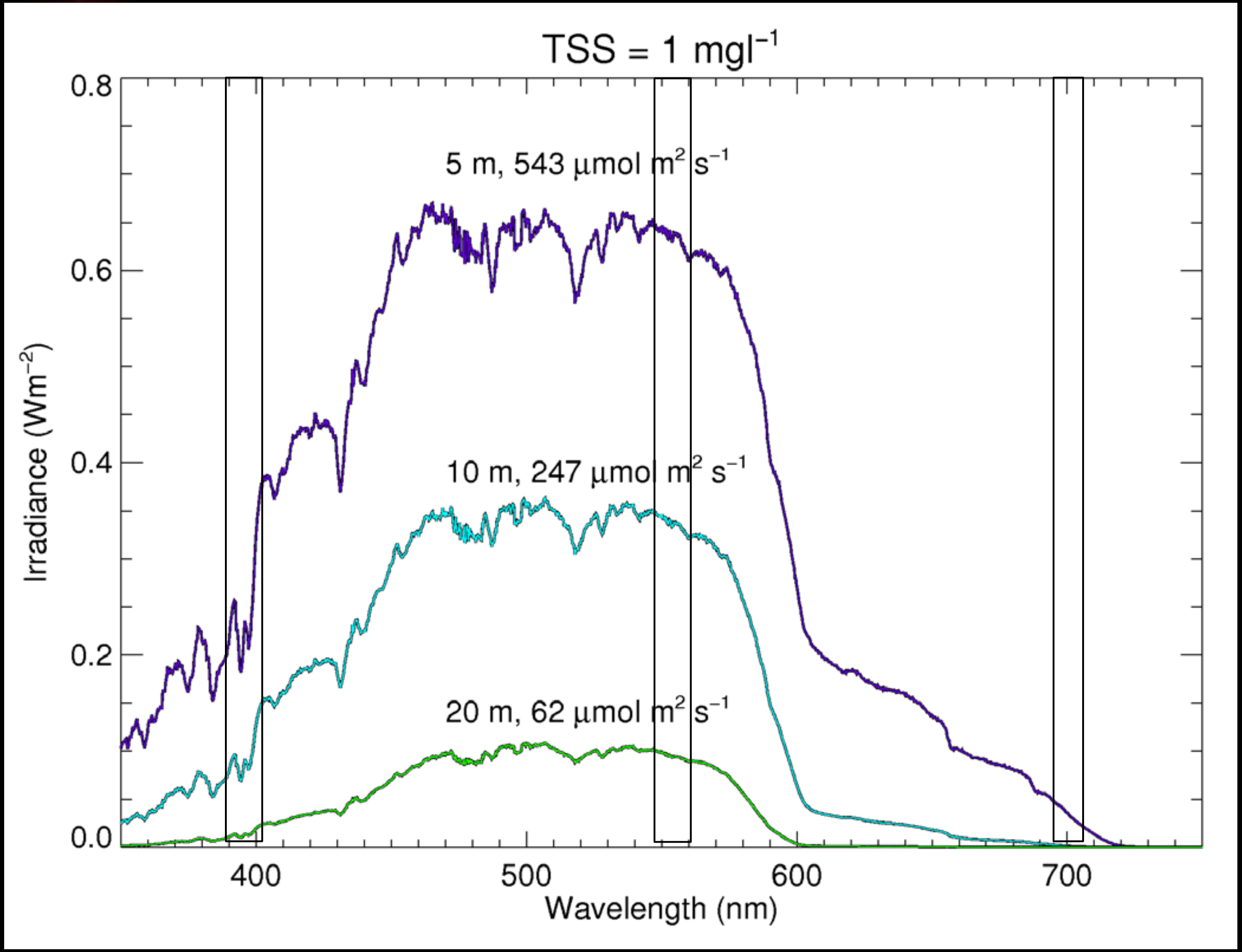
Model fitting to calculate PAR Diffuse Attenuation Coefficient (K_{dPAR})



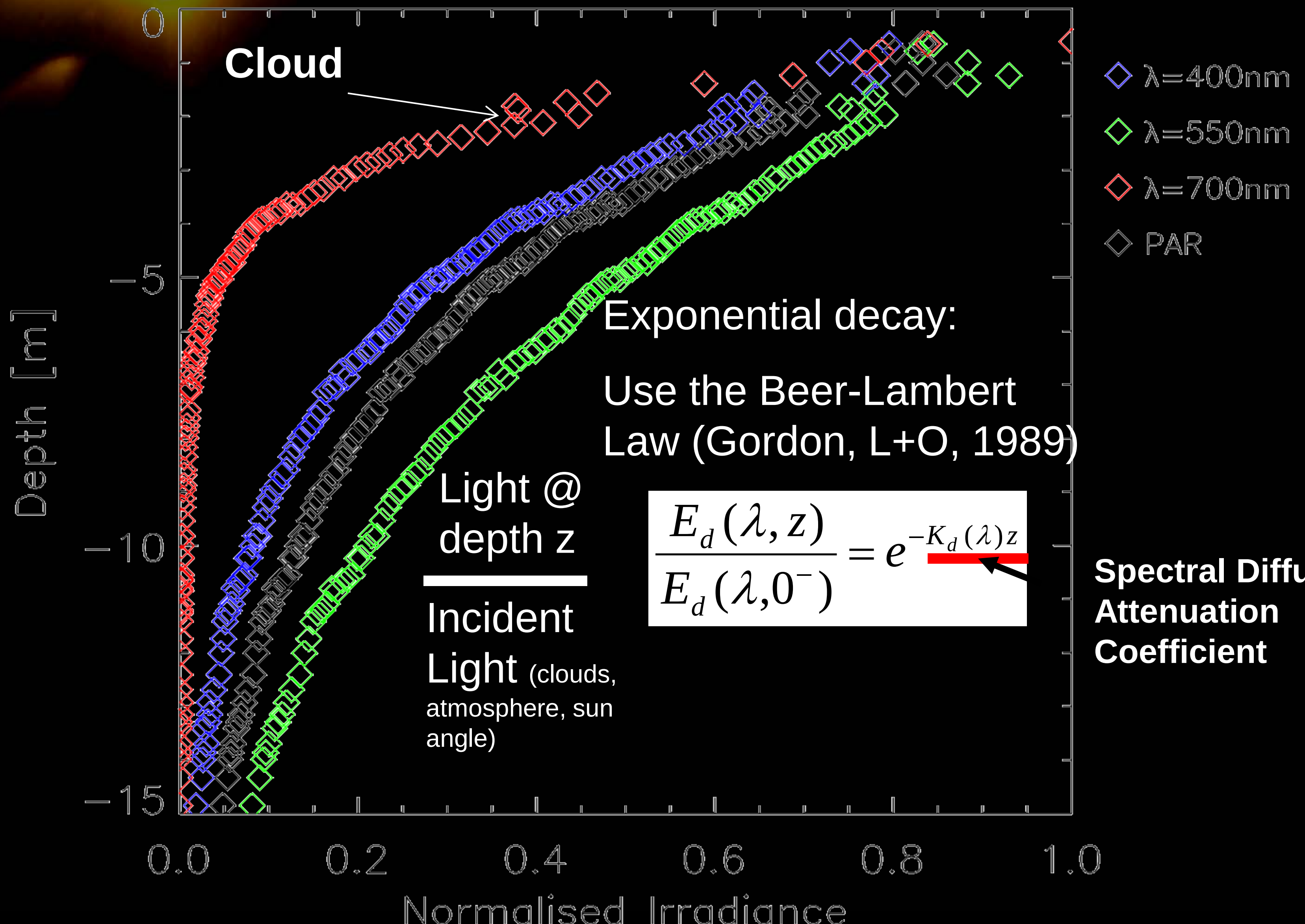
Spectral Irradiance



Spectral Irradiance



Modelling Light



Exponential decay:

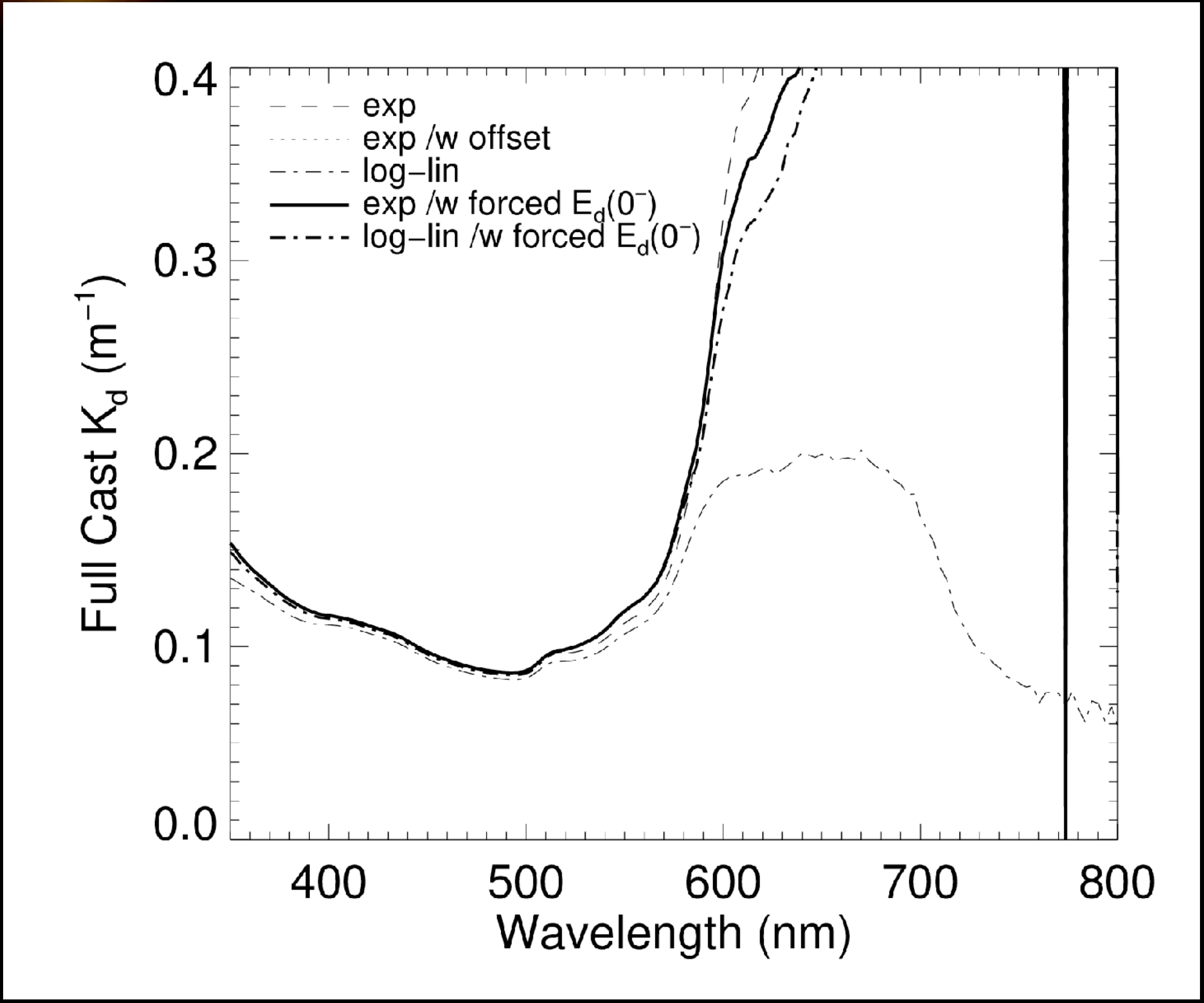
Use the Beer-Lambert Law (Gordon, L+O, 1989)

$$\frac{E_d(\lambda,z)}{E_d(\lambda,0^-)} = e^{-K_d(\lambda)z}$$

Light @ depth z / Incident Light (clouds, atmosphere, sun angle)

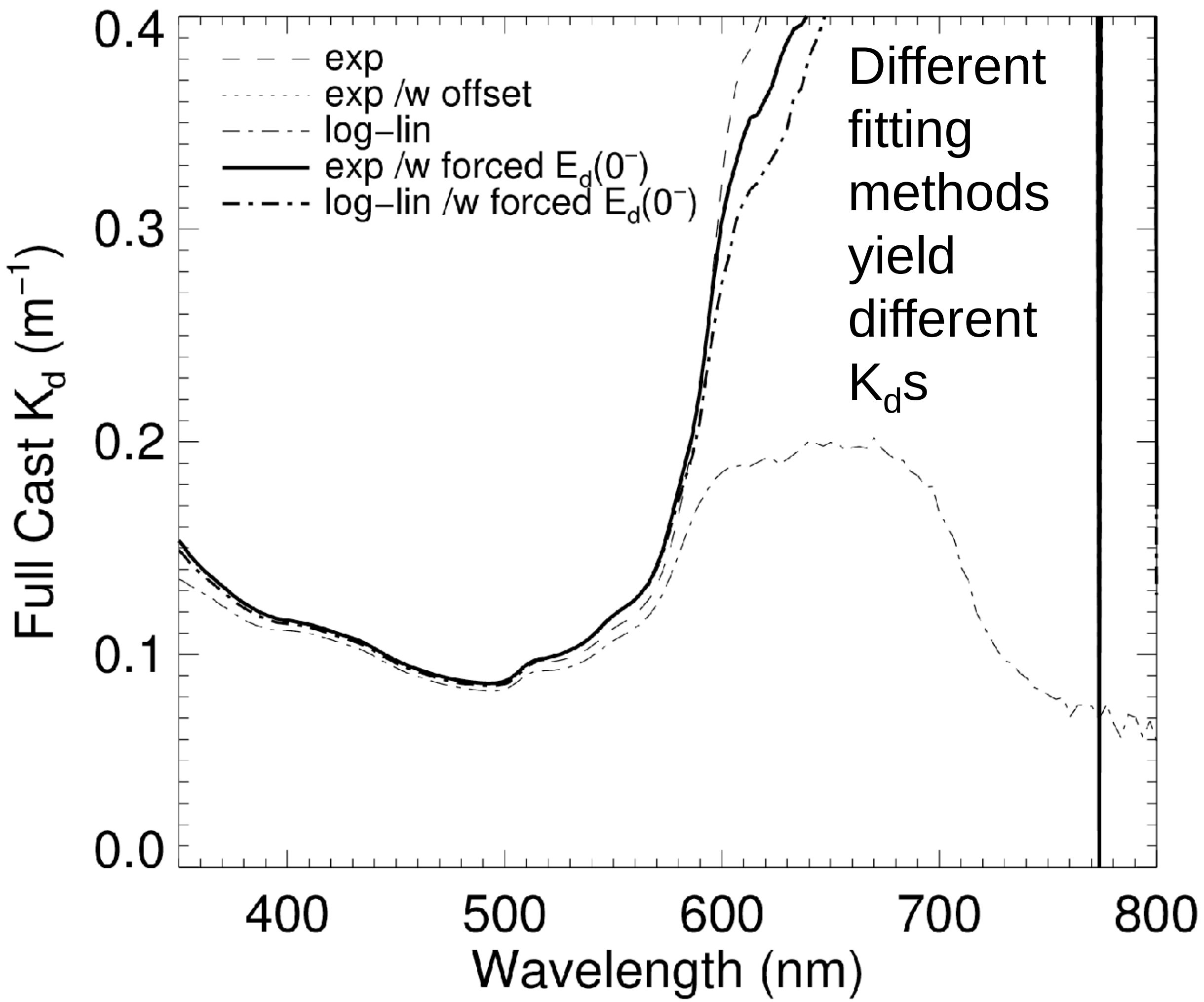
Spectral Diffuse Attenuation Coefficient

Spectral K_d



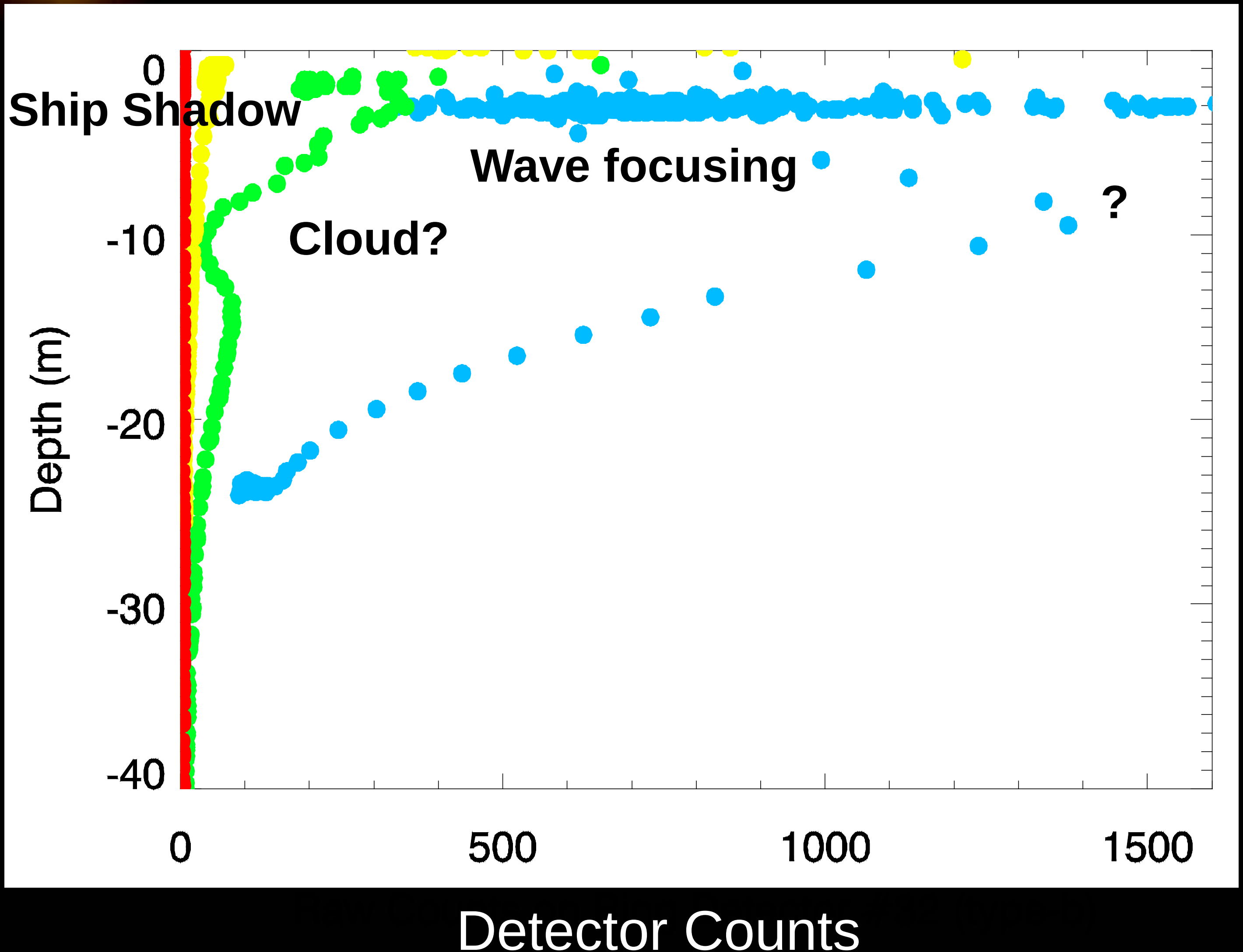
exp
exp /w offset
log–lin
exp /w forced E$_d$(0$^-$)
log–lin /w forced E$_d$(0$^-$)
Full Cast K$_d$ (m^{-1})
0.0
0.1
0.2
0.3
0.4
400
500
600
700
800
Wavelength (nm)

Spectral K_d



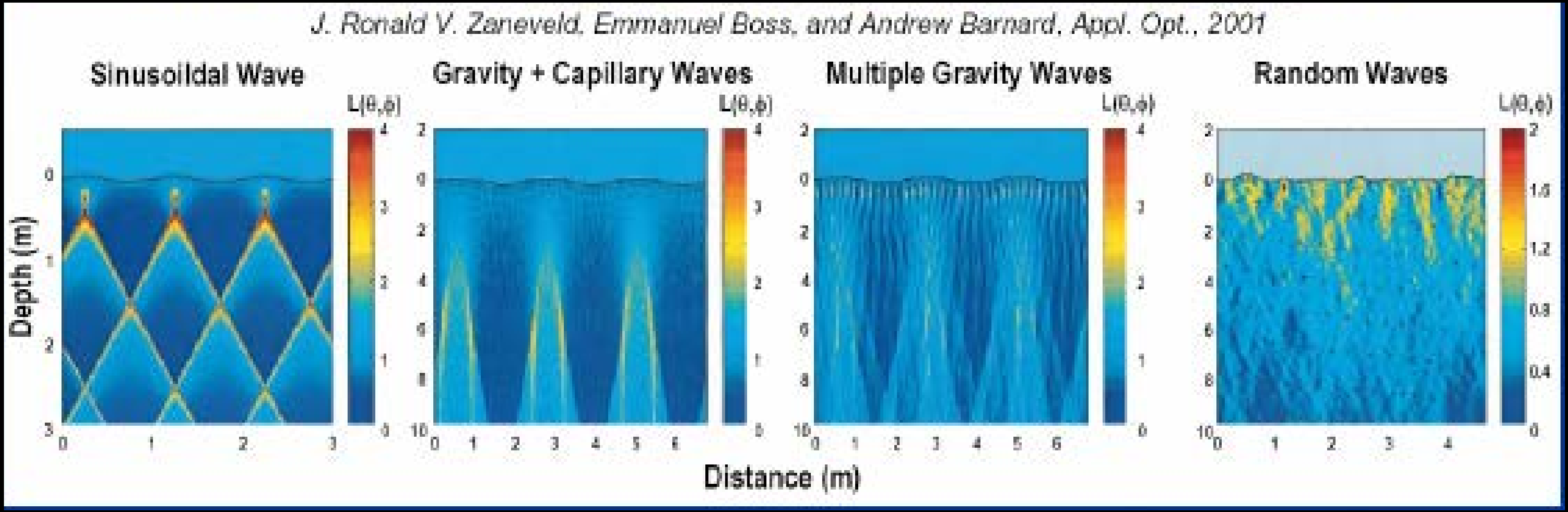
Different fitting methods yield different K_ds

Bad Profiles



Waves

- Influence of waves on radiance distribution



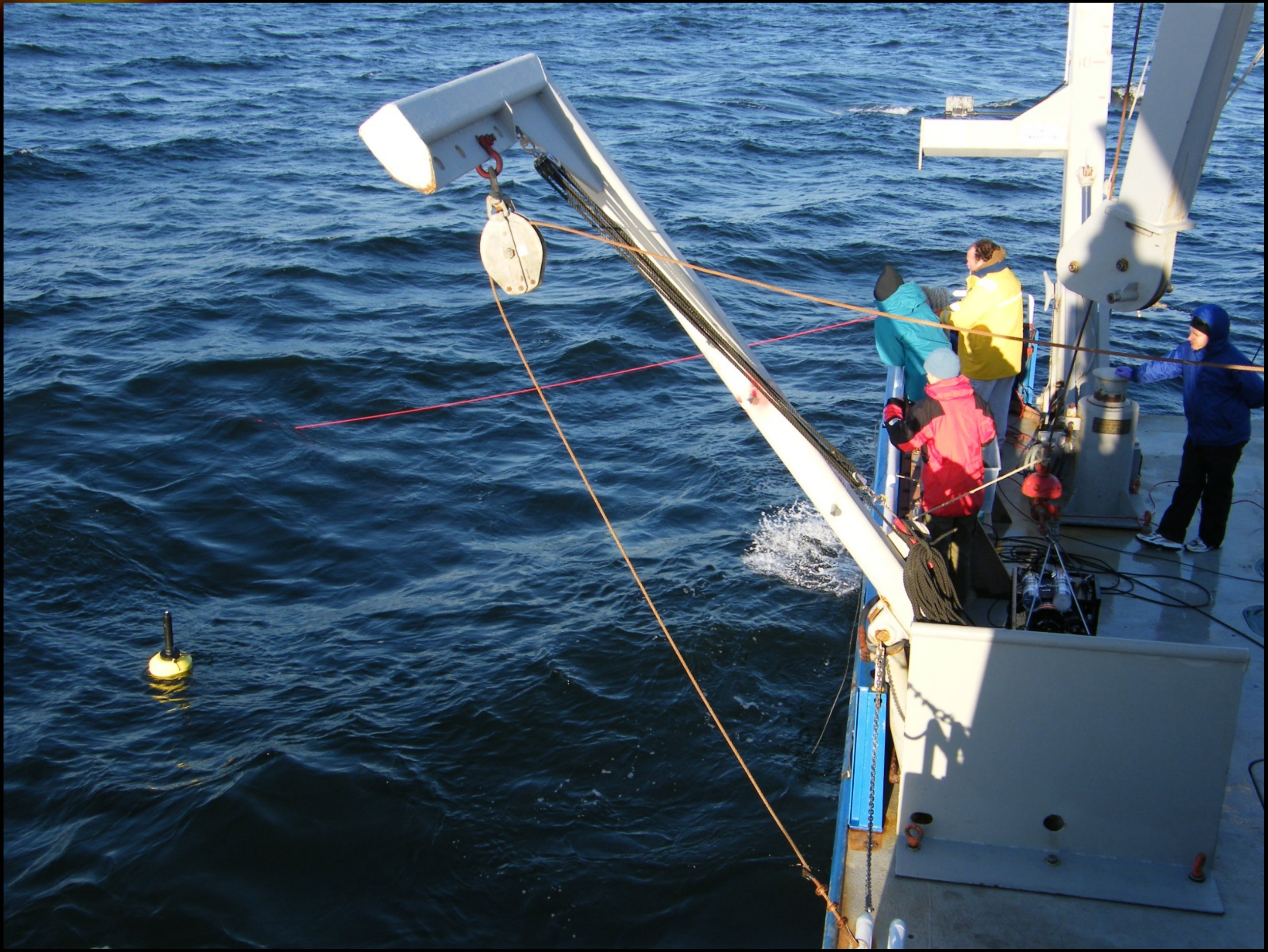
- Average multiple casts
- Longer casts
- Build cooler toys

Ship Shadow

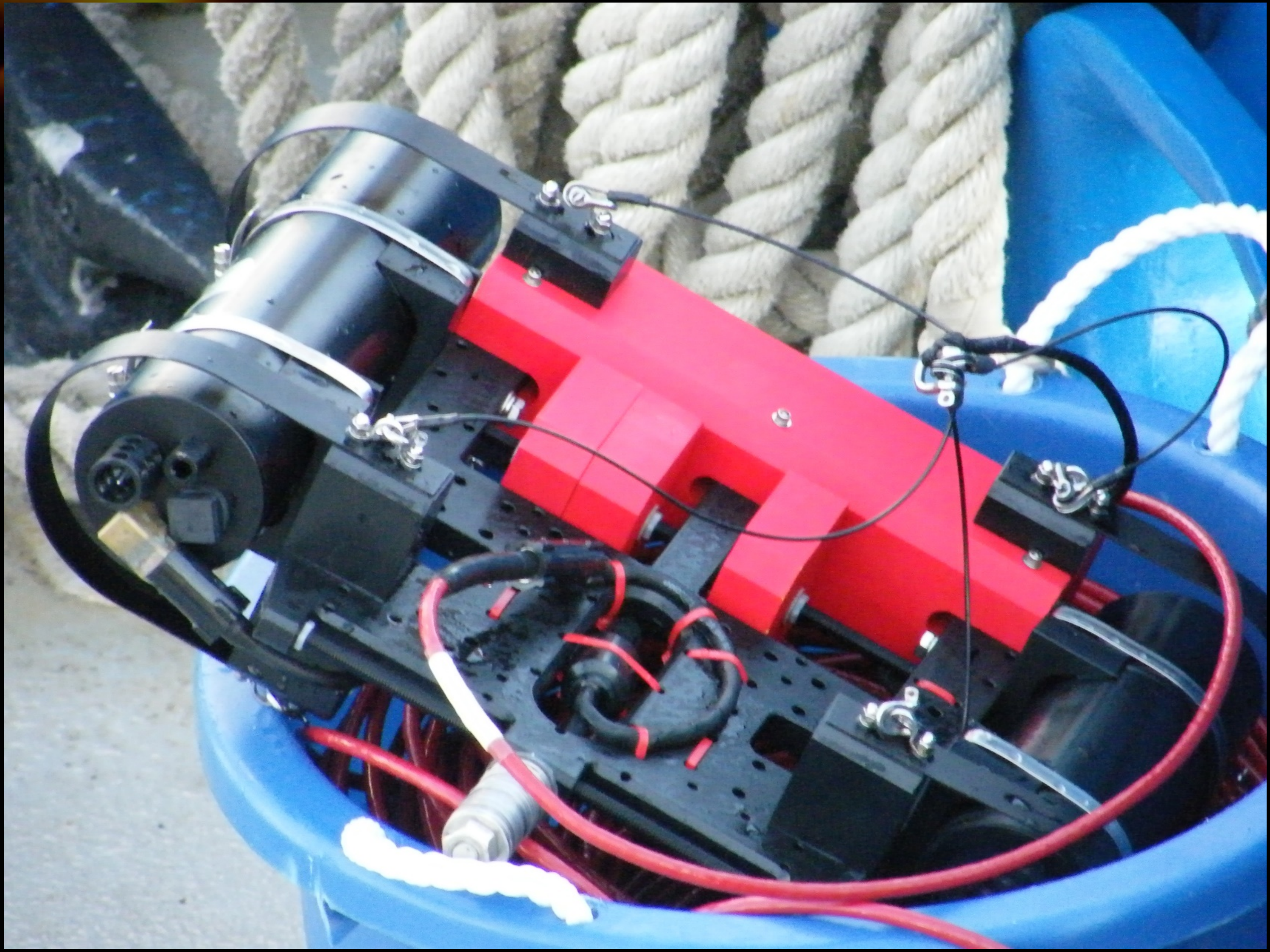
- NASA OO Protocols recommend measuring radiometric profiles a certain distance away from the ship…

E_d E_u L_u

Ship Shadow

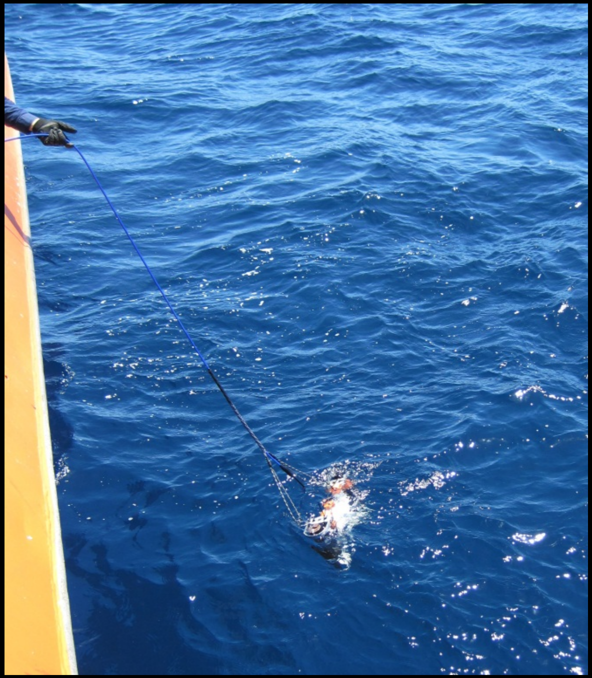


Irradiance Profiler

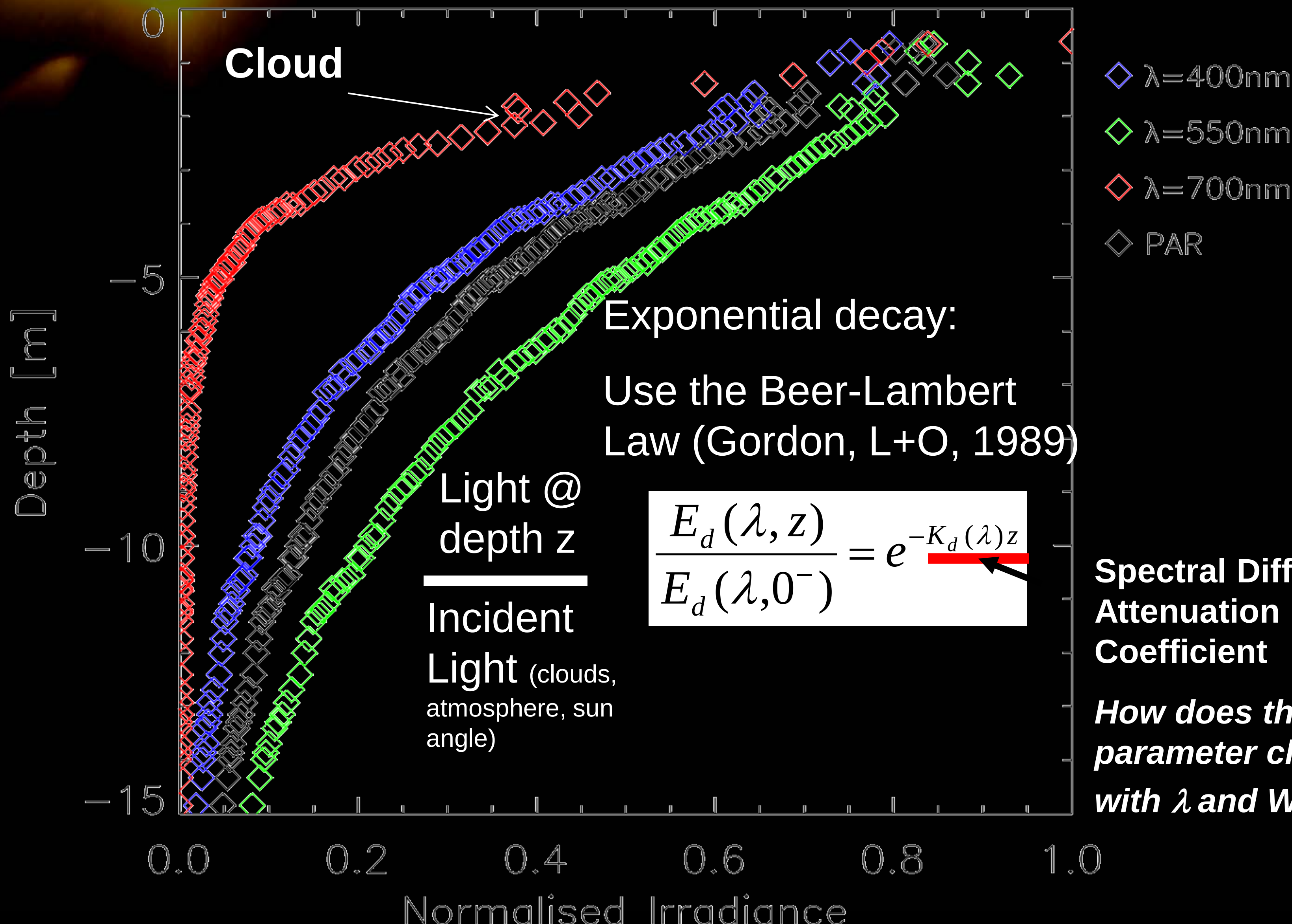


Vertical Irradiance Profiler

Vertical Irradiance Profiler



Modelling Light



Exponential decay:

Use the Beer-Lambert Law (Gordon, L+O, 1989)

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Light @ depth z

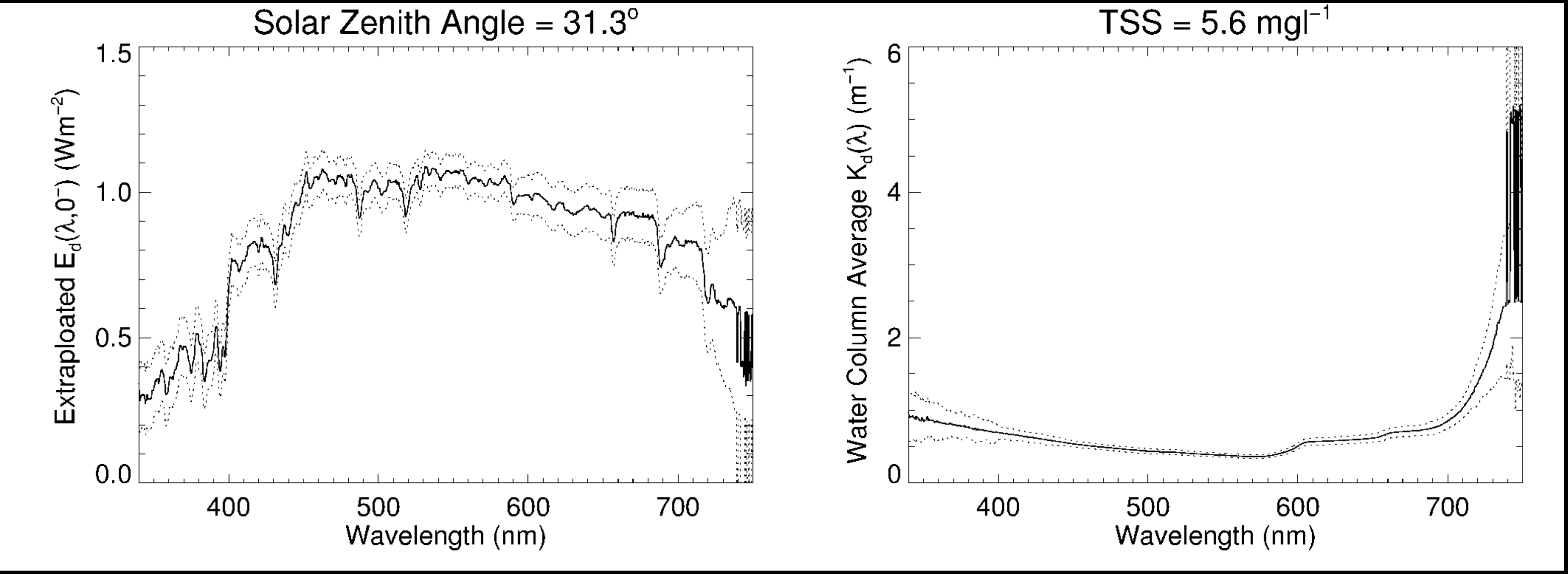
Incident Light (clouds, atmosphere, sun angle)

Spectral Diffuse Attenuation Coefficient

How does this parameter change with λ and WQ?

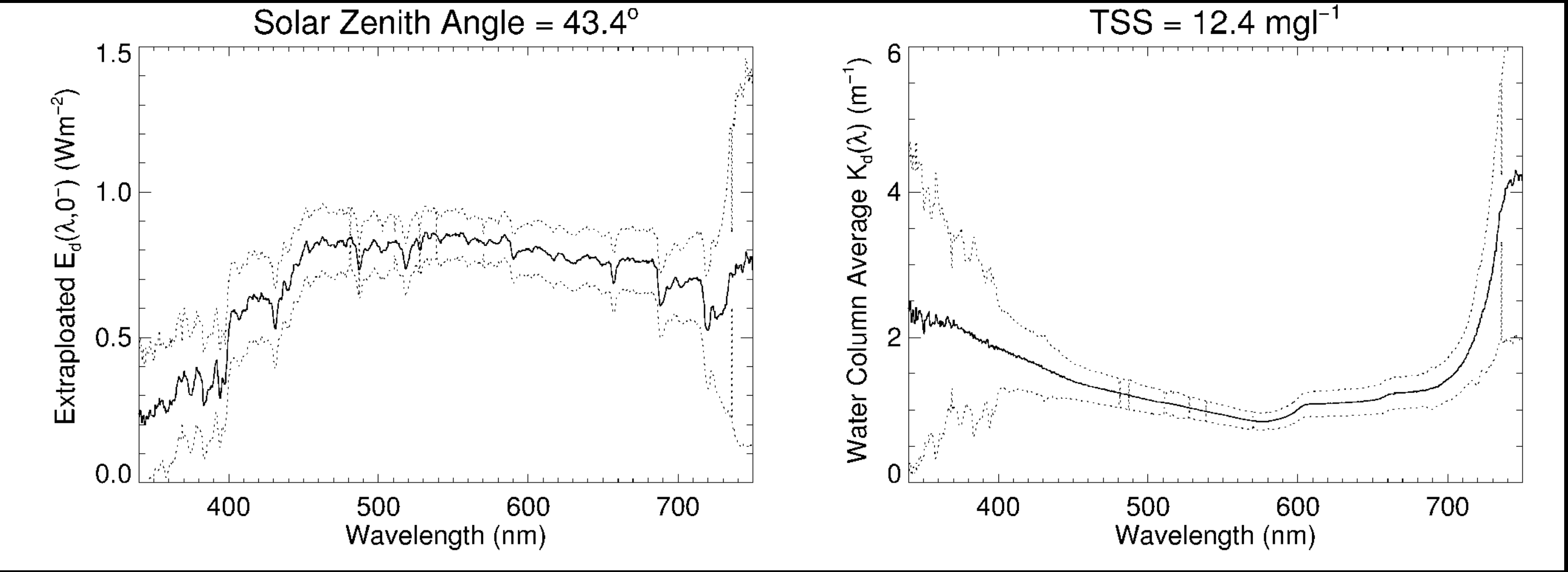
Examples

$E_d(\lambda,0^-)$ $K_d(\lambda)$



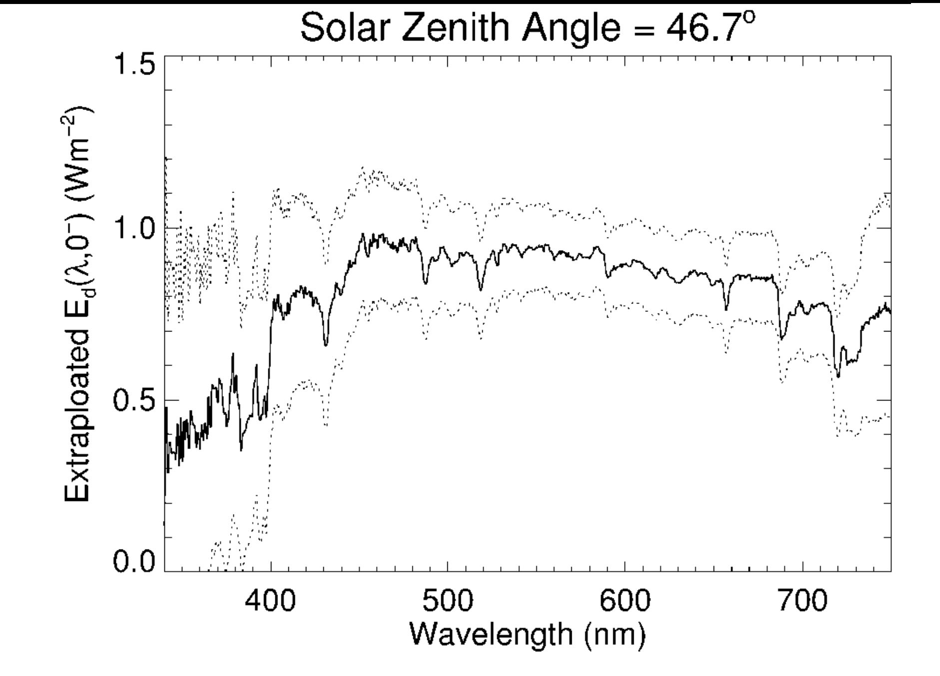
Examples

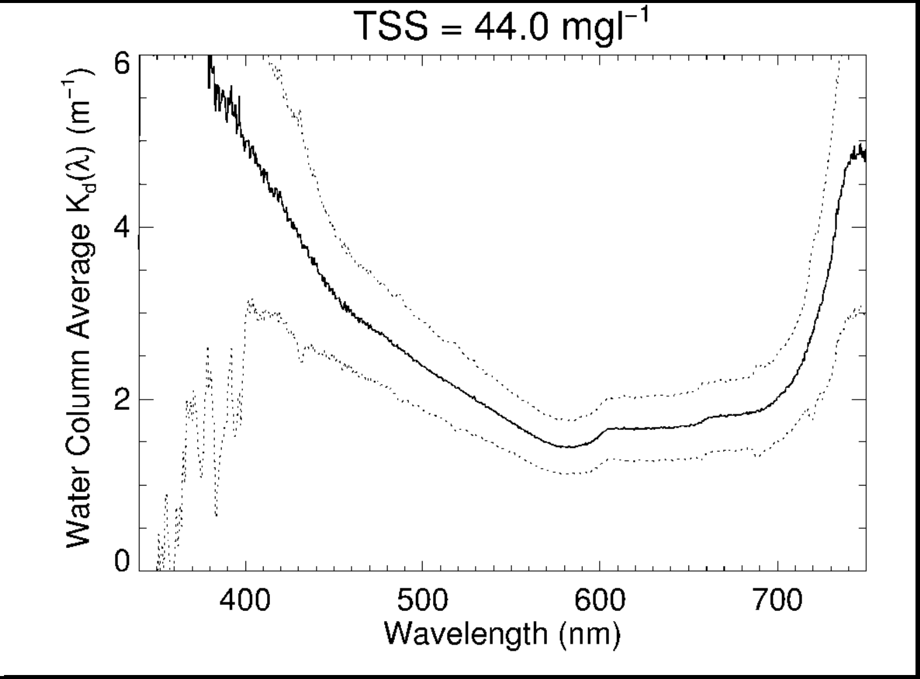
$E_d(\lambda,0^-)$ $K_d(\lambda)$



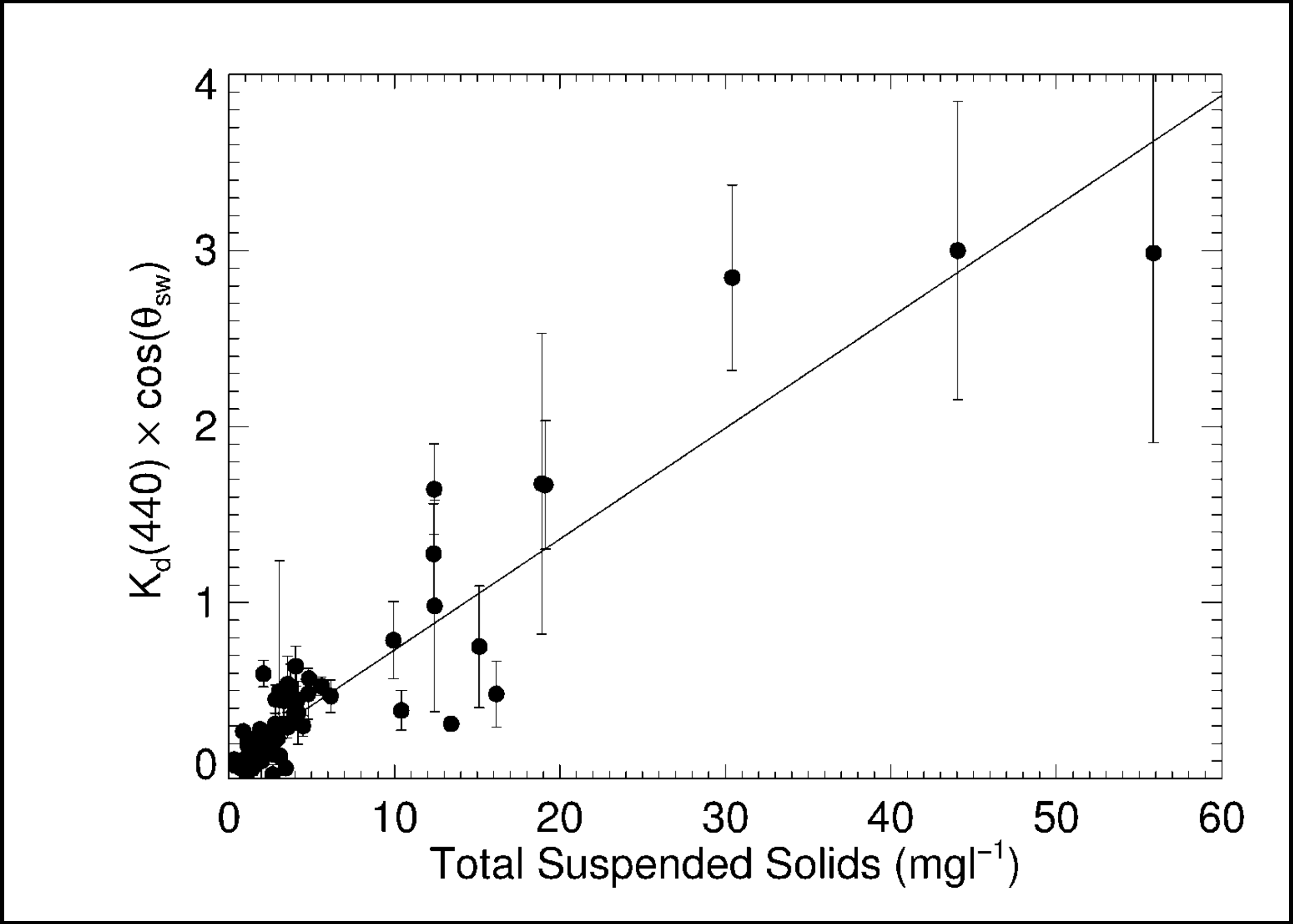
Examples

$E_d(\lambda,0^-)$ $K_d(\lambda)$



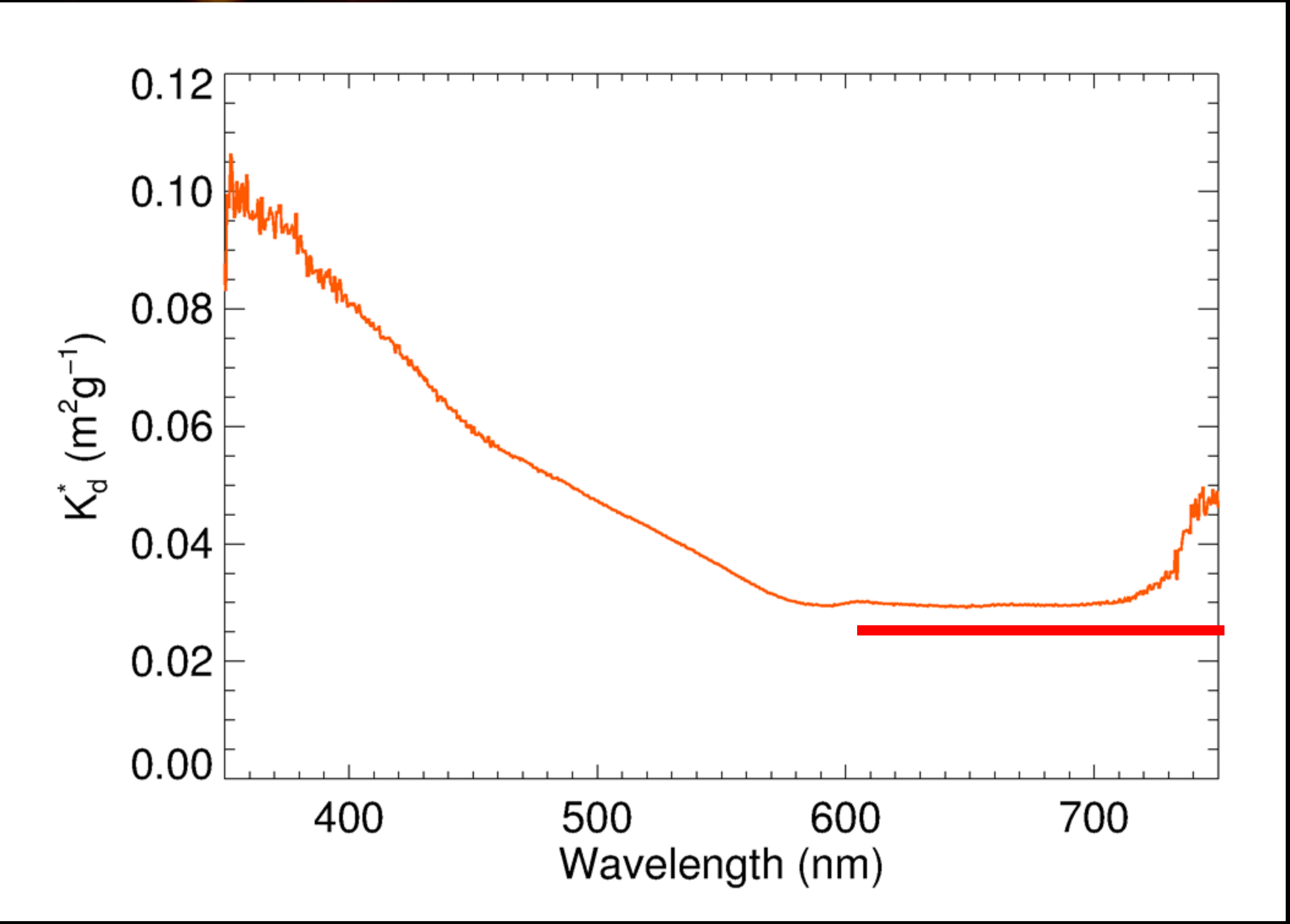


K_d related to TSS/M?



x error bars ~ sd of triplicates omitted for clarity

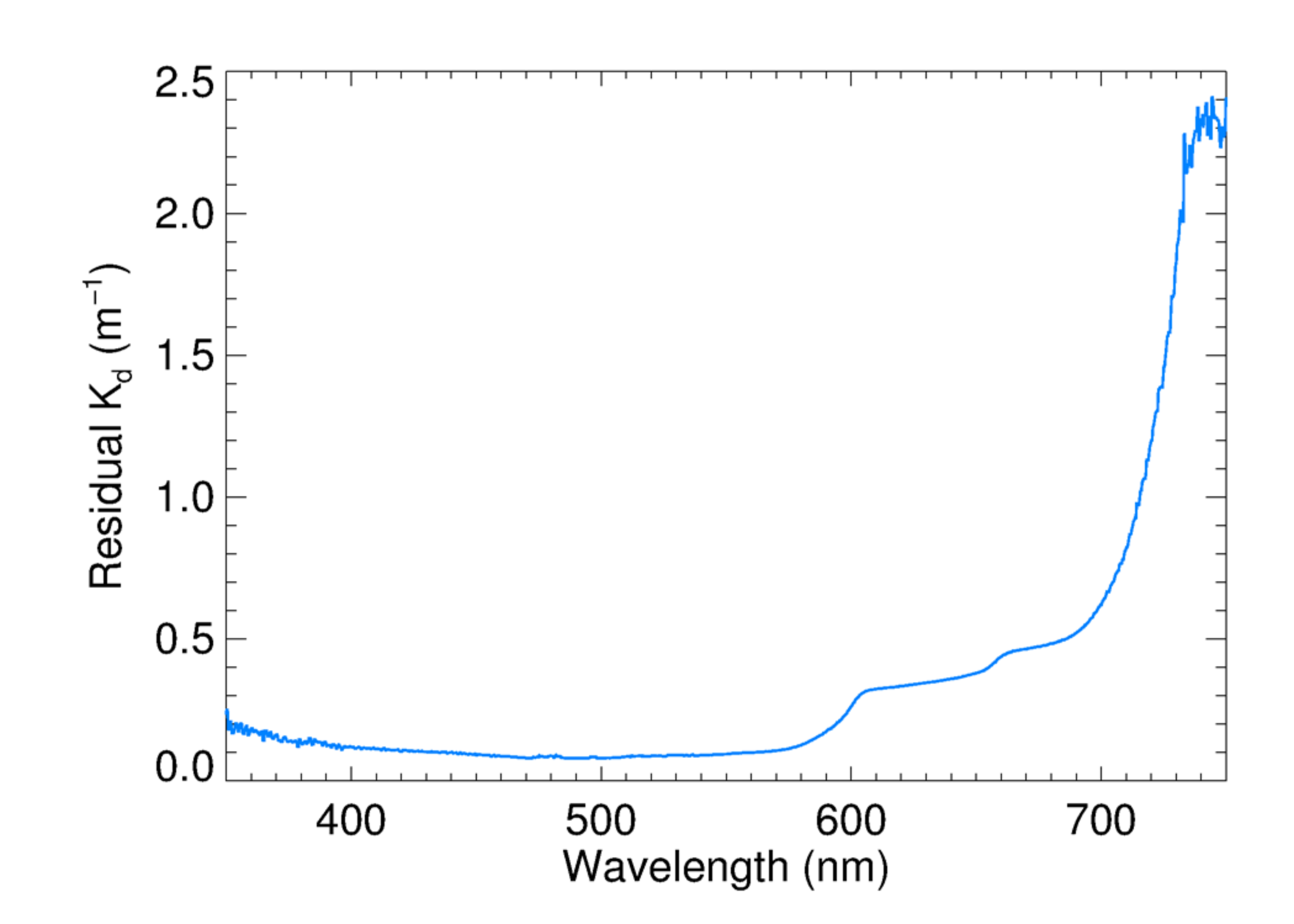
TSS Specific $K_d(\lambda)$



Spectral artifacts. Water drives the attenuation in the NIR

Spectral shape similar to non-algal particulate absorption

Residual Attenuation



Similar to water absorption spectral shape + residual

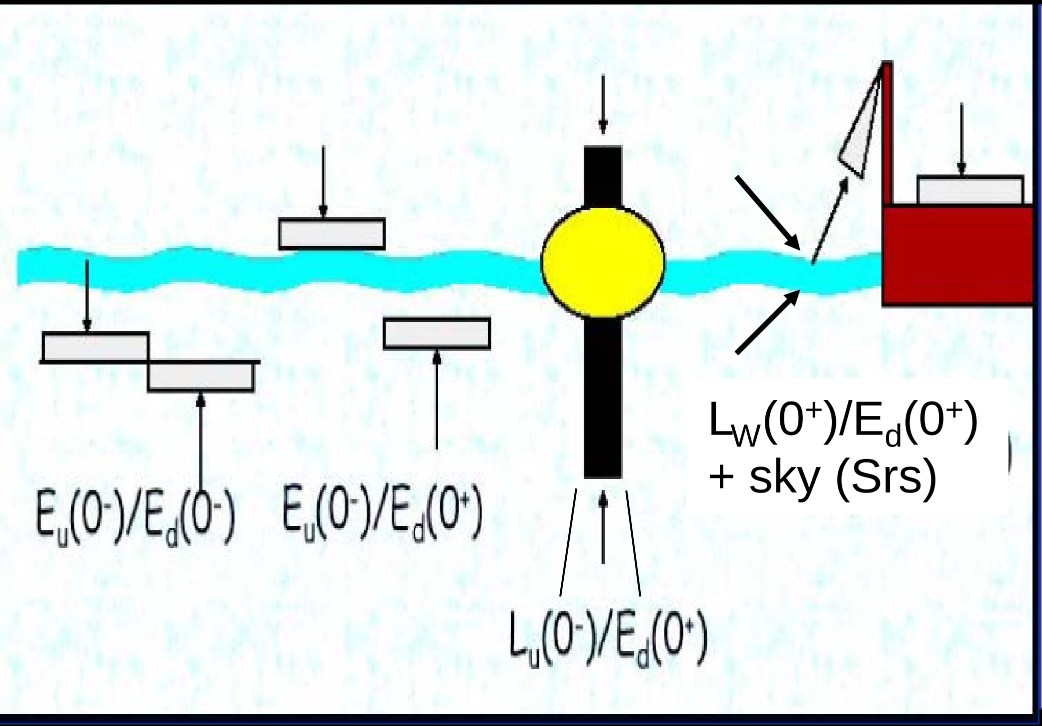
K_d Uncertainty Summary

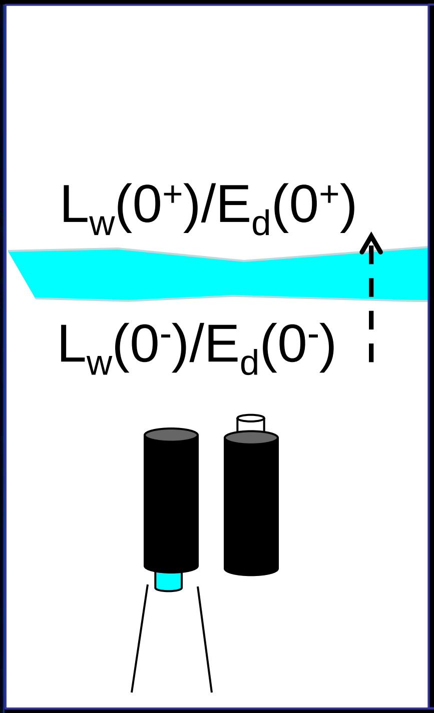
- Incident $E_d(0^+)$ influenced by clouds
  - Get an above-water $E_d(0^+)$, time stamped to the in-water E_d sensor
  - Only sample in clear skies
- Temporal Variability
  - Wave focusing – repeat casts
  - Sun transit (Kd influenced by pathlength elongation)
- Cosine collector / package tilt
  - Slow descent / free fall package
- Spatial variability
  - Repeat casts to assess
- Ship Shadow
  - Use small ship or slow descent / free fall platform
- Model fitting technique.
  - Avoid ‘black box’ fitting (i.e. excel)
  - Avoid log transformations
  - Consider weighting model fits to experimental uncertainties

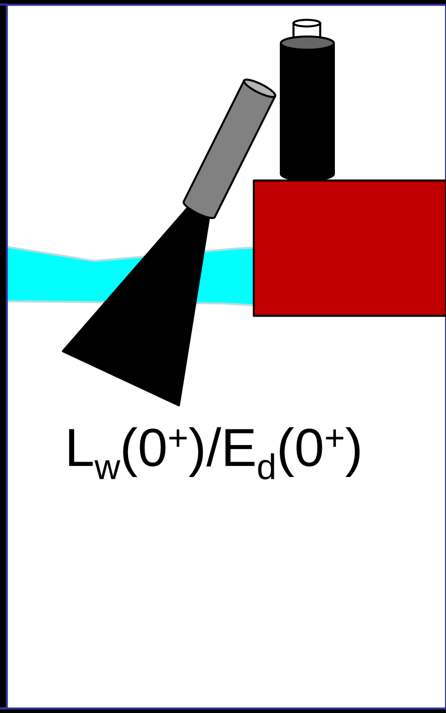
Reflectance

Irradiance Reflectance R

Remote Sensing Reflectance R_{rs}







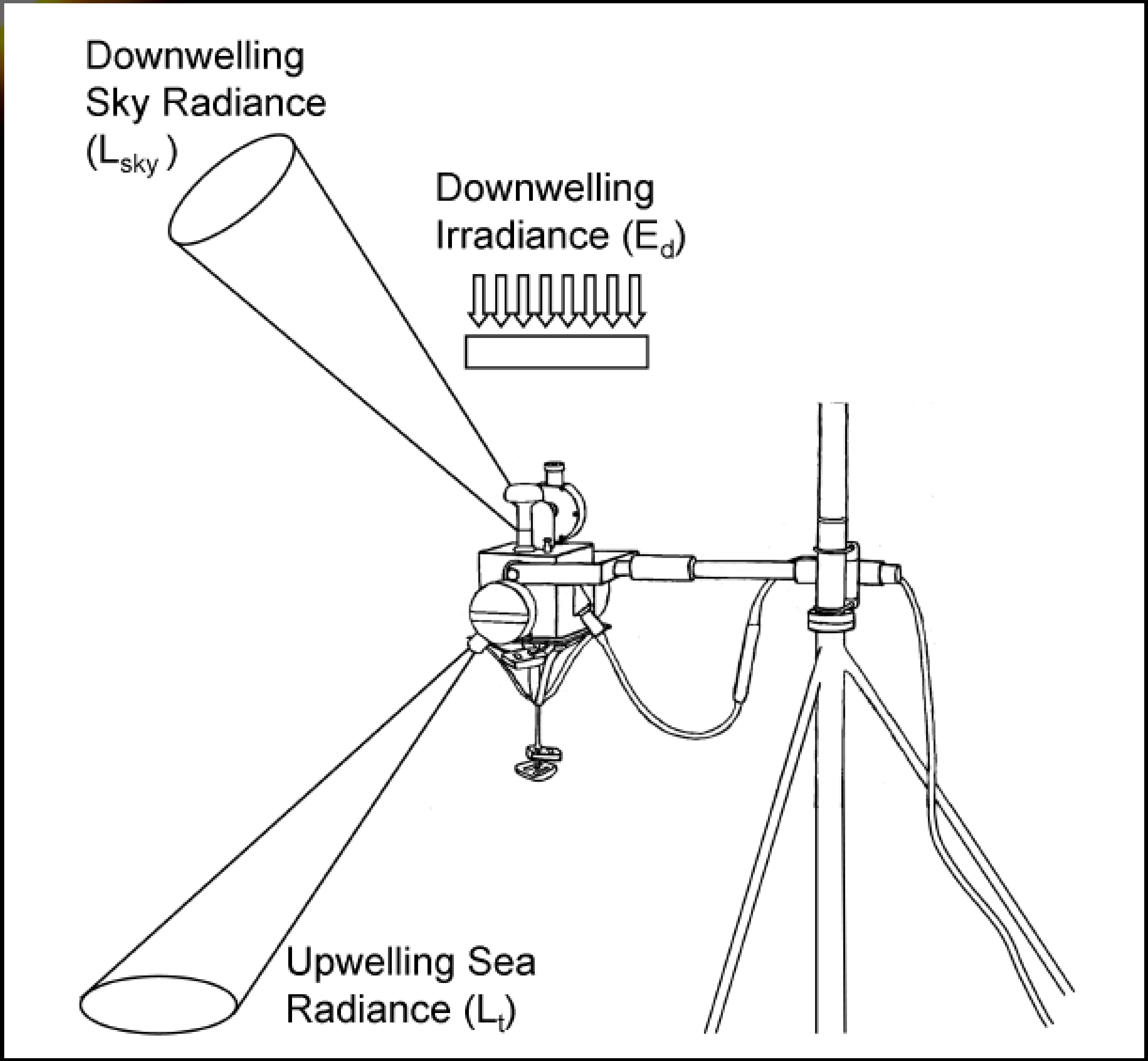
Importance of Reflectance

- Normalised by E_d, so less dependent on solar geometry, more on IOPS.
- R_{rs} can be estimated from Space
  - Provided in the form of images
  - Synoptic, Long time series data
    - CZCS ~1979?
    - SeaWiFS since 1997
    - MODIS(Terra) since 1999
    - MODIS(AQUA) since 2002
    - VIIRS, OLCI etc…
- In-situ R_{rs} for validation?

$$R_{rs} \sim func\left(\frac{b_b}{a+b_b}\right)$$

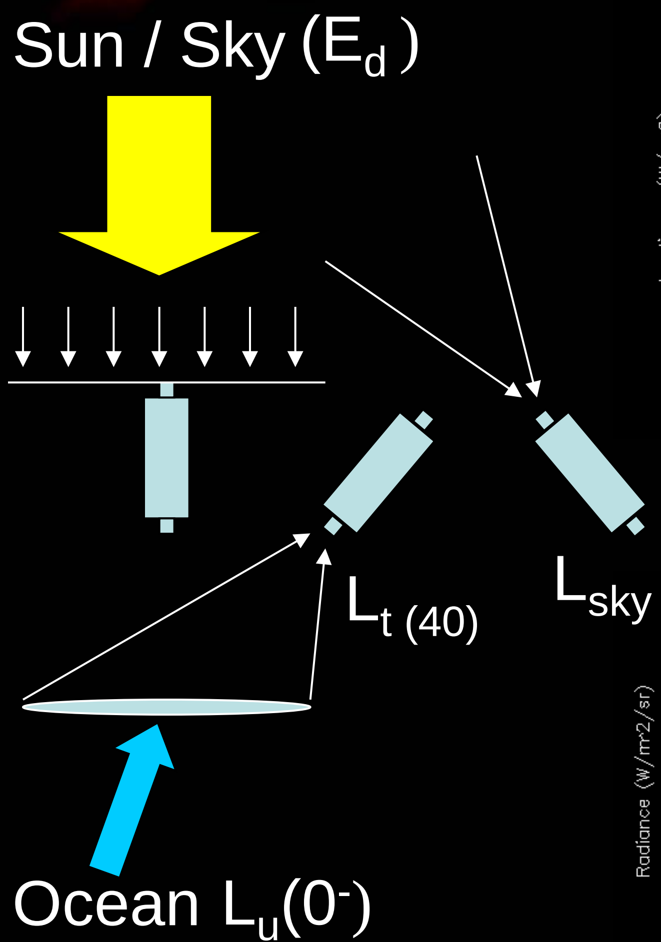
wavelength omitted

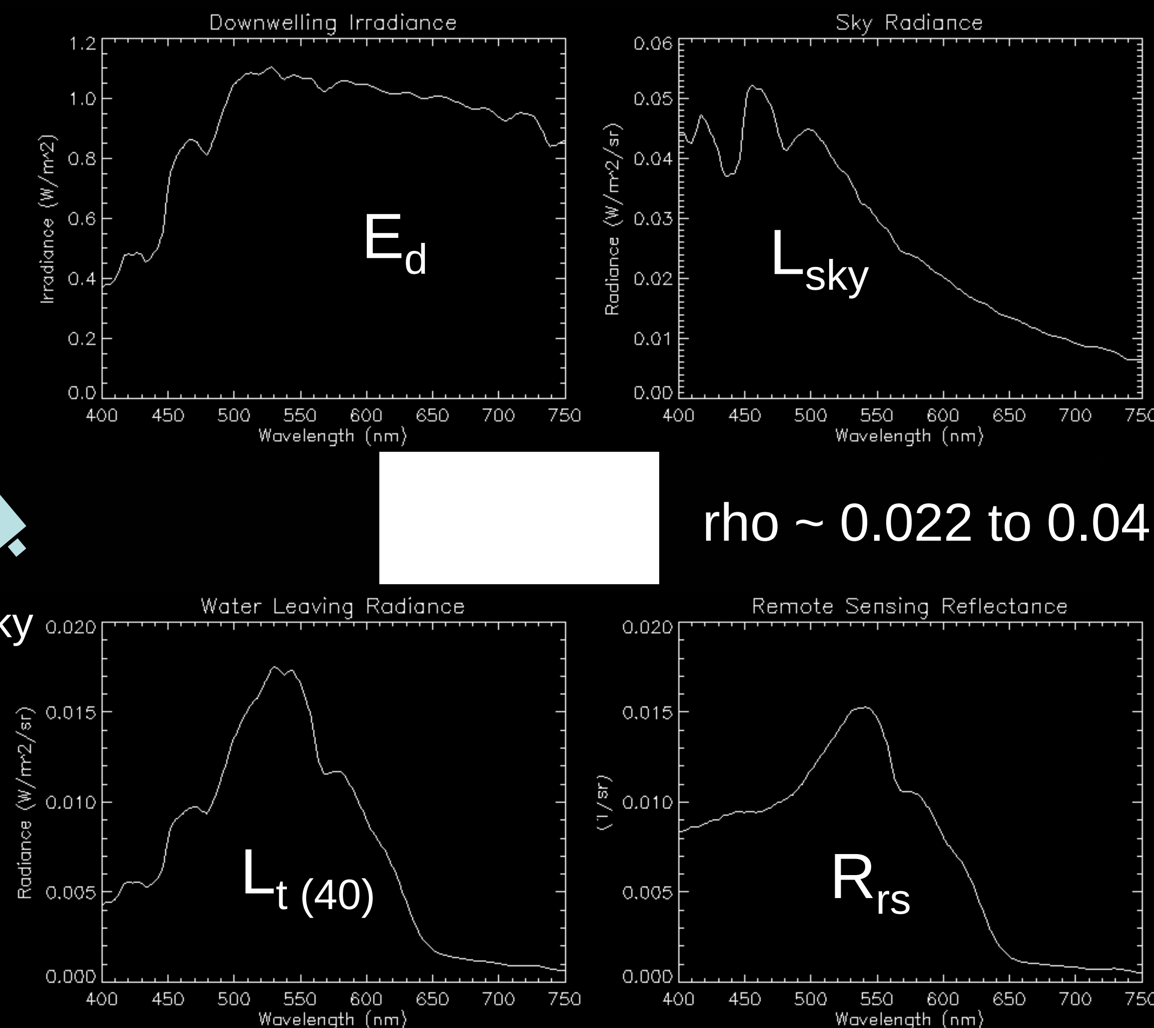
In-situ Reflectance (R_{rs})



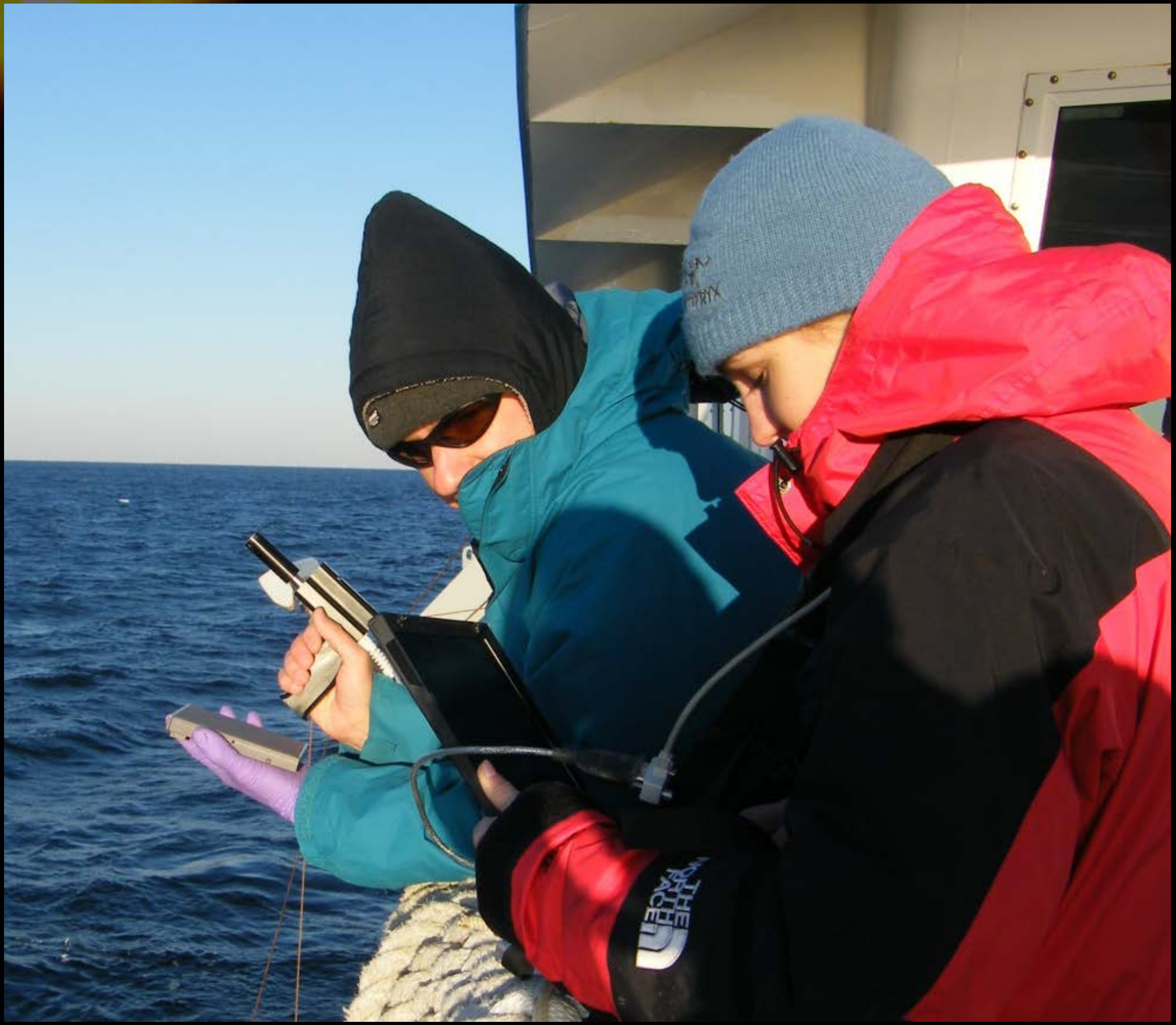
Downwelling
Sky Radiance
(L_{sky})
Downwelling
Irradiance (E_d)
Upwelling Sea
Radiance (L_t)

Constituent Measurements to approximate R_{rs}



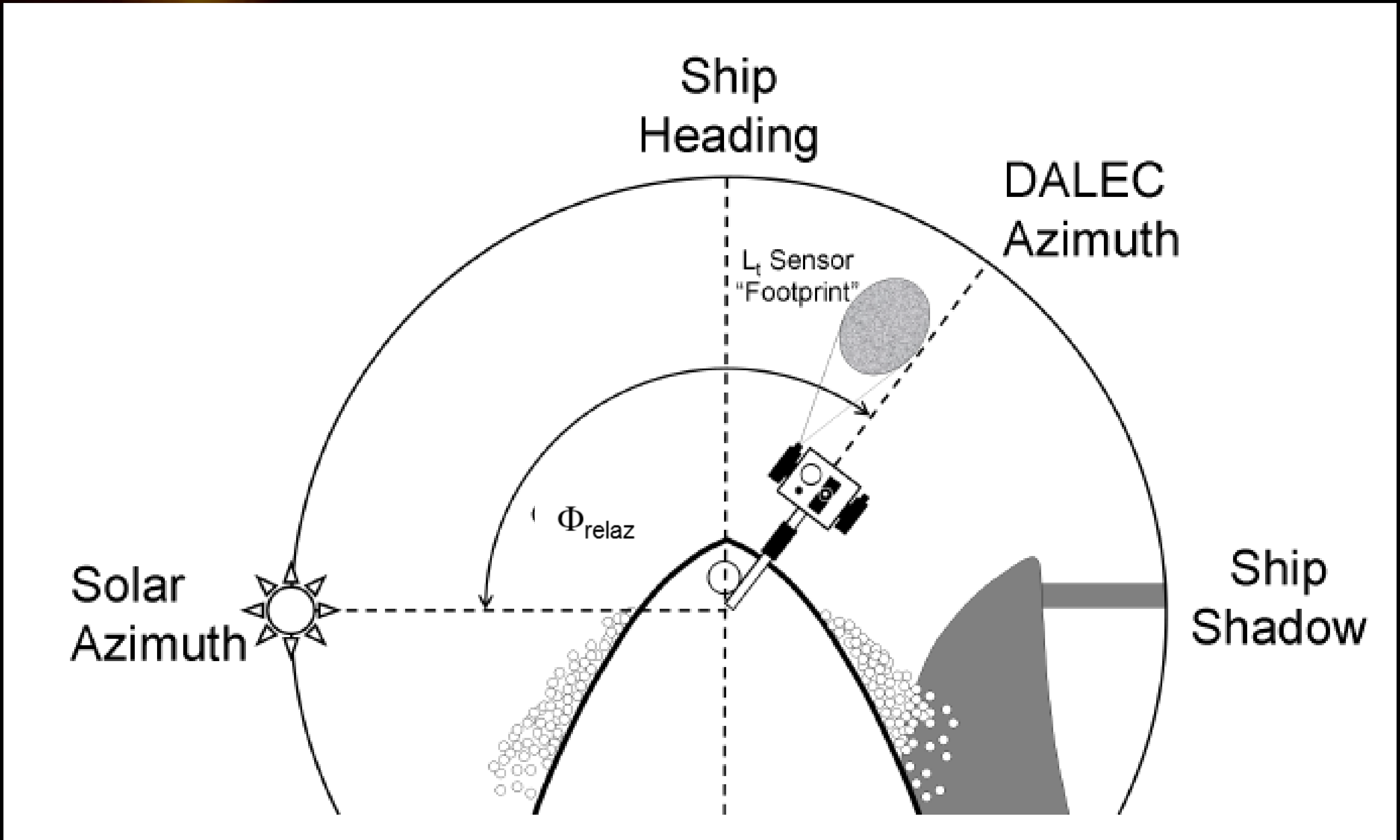


rho ~ 0.022 to 0.04



Plaque method (10% grey)

Top View

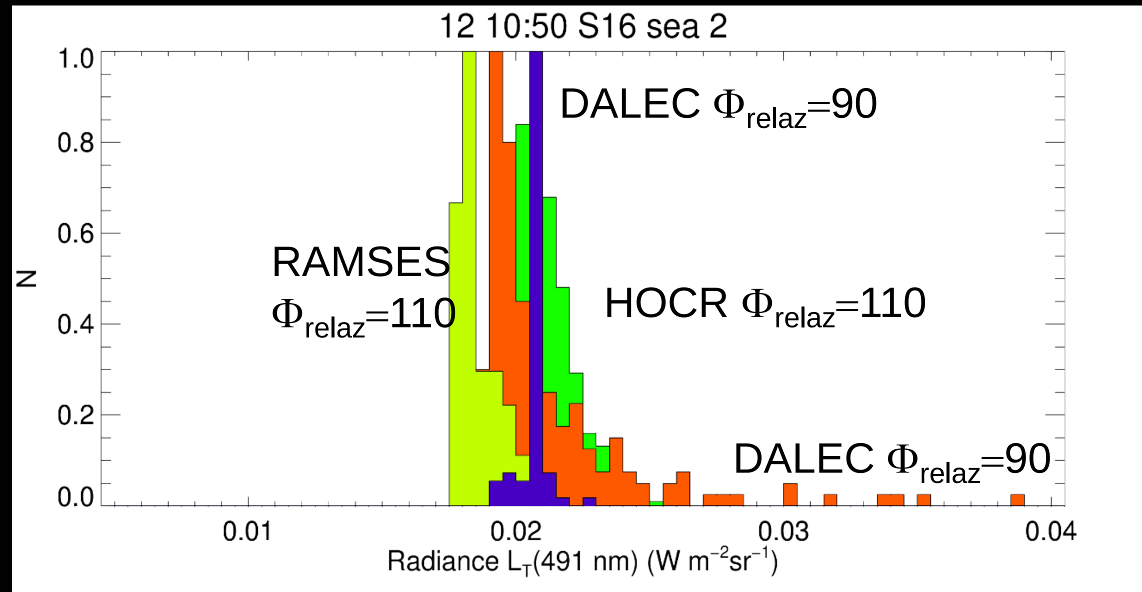


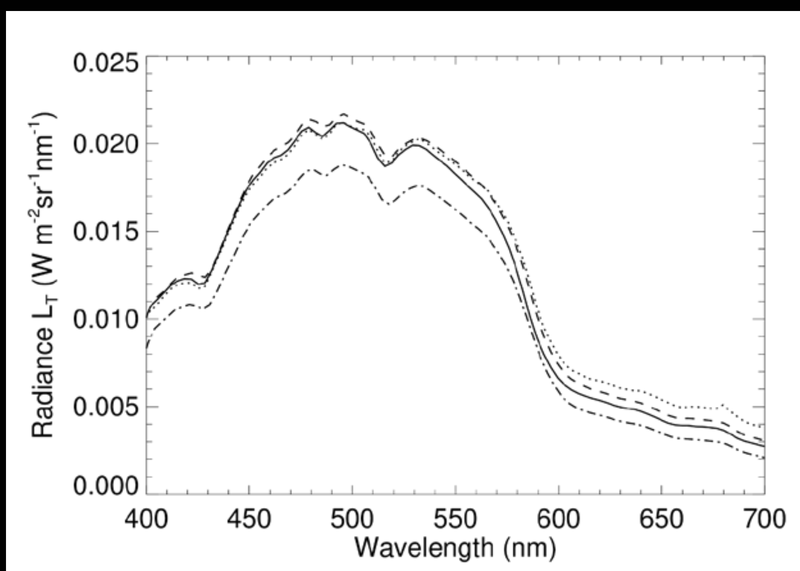
$$R_{rs} = \frac{L_w}{E_d} = \frac{L_t - \rho(\lambda, \phi_{az}, U, \theta_z) L_{sky}}{E_d},$$

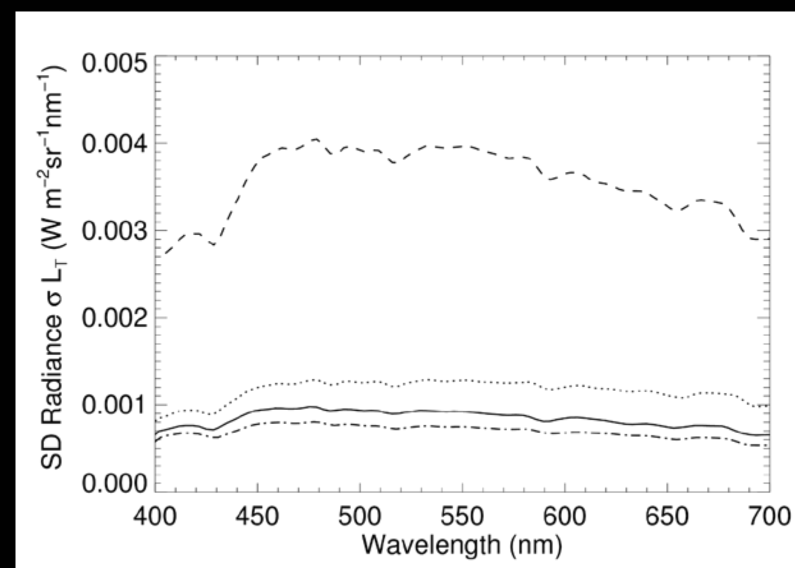
see Mobley 1999, Zibordi et. al. 2002, Ruddick 2005/6 and Lee et. al. 2010

Skylight Contamination

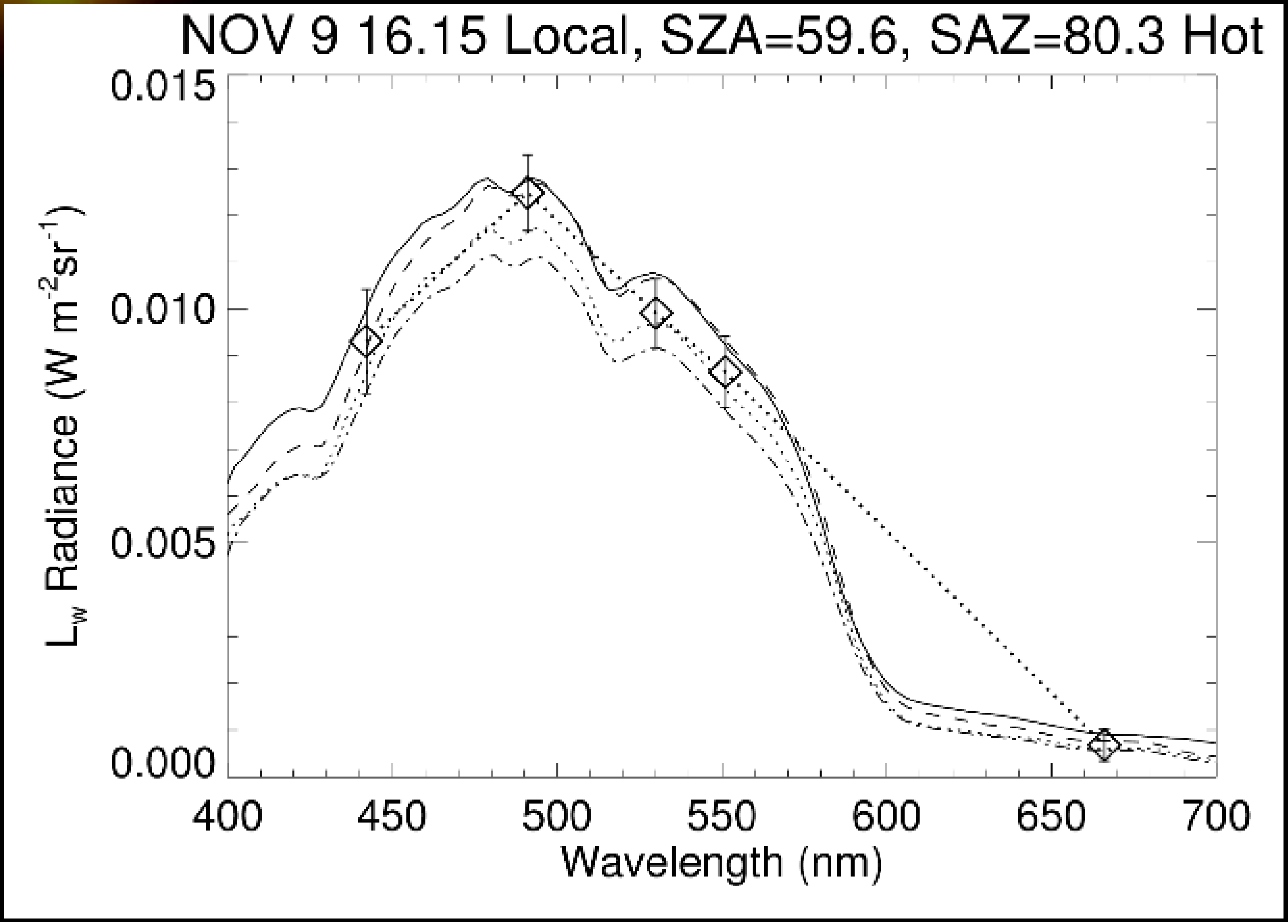
- Sea viewing radiance spectra contains flashes of reflected skylight/glint, originating from a range of angles, centred around the complementary view angle
- Range of angles depends on wind speed, view angle, SZA, sun relative azimuth angle and sensor FOV
- In terms of reflectance, this contamination reduces to a power law with a spectrally independent offset


12 10:50 S16 sea 2
DALEC Φ_{relaz}=90
RAMSES Φ_{relaz}=110
HOCR Φ_{relaz}=110
DALEC Φ_{relaz}=90
N
1.0
0.8
0.6
0.4
0.2
0.0
0.01
0.02
0.03
0.04
Radiance L_T(491 nm) (W $m^{-2}sr^{-1}$)


Radiance L_T (W $m^{-2}sr^{-1}nm^{-1}$)
0.025
0.020
0.015
0.010
0.005
0.000
400
450
500
550
600
650
700
Wavelength (nm)


SD Radiance σ L_T (W $m^{-2}sr^{-1}nm^{-1}$)
0.005
0.004
0.003
0.002
0.001
0.000
400
450
500
550
600
650
700
Wavelength (nm)

Corrected



NOV 9 16.15 Local, SZA=59.6, SAZ=80.3 Hot
0.015
0.010
0.005
0.000
400
450
500
550
600
650
700
Wavelength (nm)
L_w Radiance (W m^{-2}sr^{-1})

Uncertainties in Rrs

- Instrumental
  - Discussed earlier
  - Ratio means temperature errors may cancel
- Methodological
  - Temporal changes (sequential or simultaenous E_d, L_u and L_{sky})
  - Integration time
  - Skylight reflection contaminates as a function of FOV, wind speed, SZA, integration time.
  - Many different correction approaches
    - Combining a few approaches will help
  - Platform Perturbation
    - Monte Carlo “SimulO” radiative transfer code to simulate deployment scenario

The End

- Thanks for your attention
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