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Spectral variability of in-water downwelling irradiance induced by wave focusing

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Motivation

Campaigns

Small boat in shallow areas of 3 German lakes

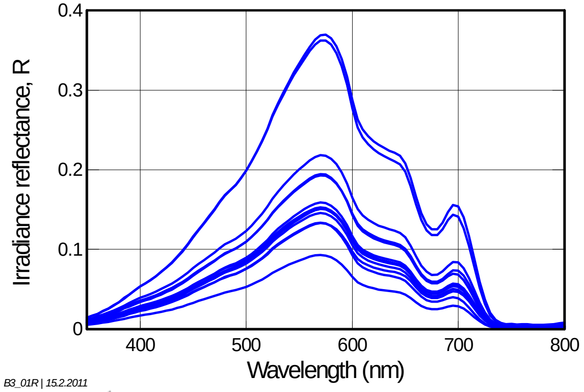
421 data sets, 4375 spectra at 0–5 m depth

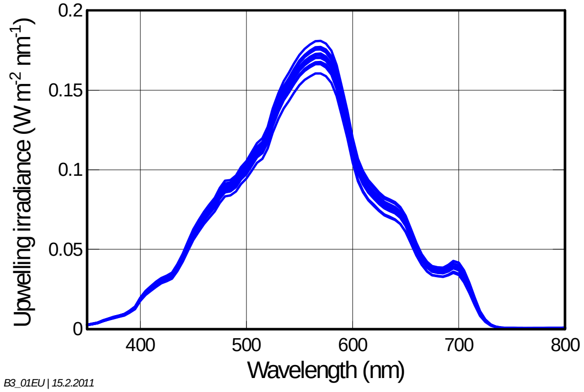
Observation

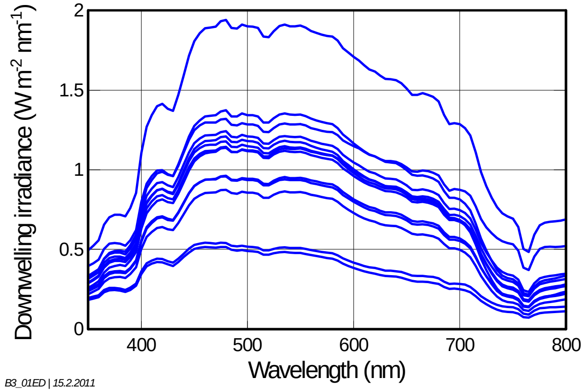
Reflectance spectra (in shallow water) can vary strongly in magnitude and spectral shape **– why?**

Bodensee 26.6.2004, 12:20
Bottom type: sediment
Water depth: 1.40 m
Sensor depth: 0.28 m
13 measurements within 65 s

Due to variability of downwelling irradiance







Spectral variability of downwelling irradiance in water induced by wave focusing

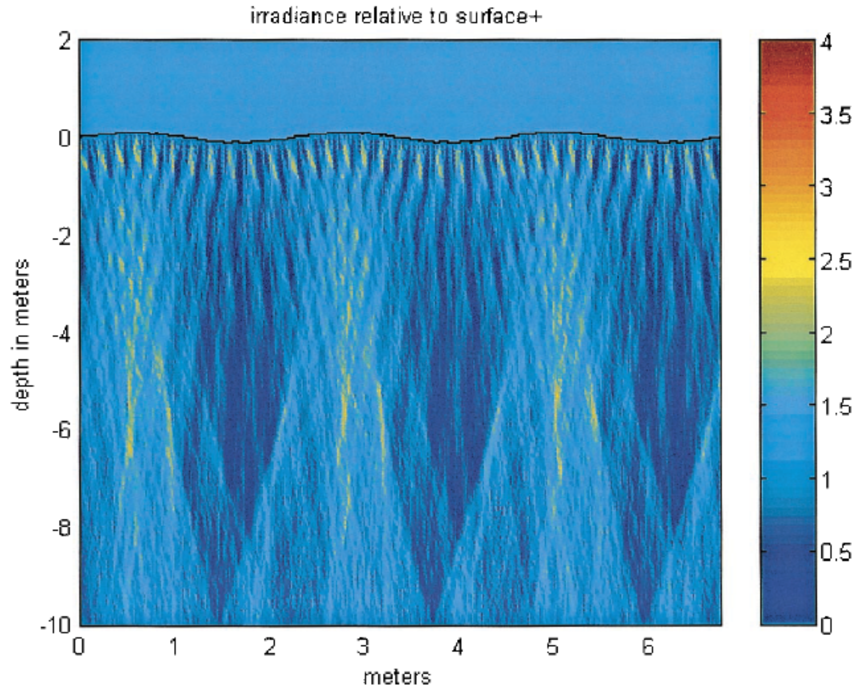


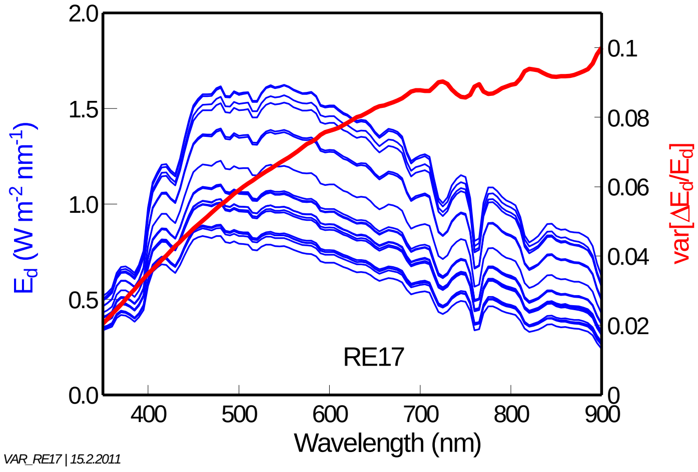
Fig. 6. Irradiance pattern beneath a superposition of sinusoidal waves with wavelengths of 2.25, 0.2, and 0.05 m and with amplitudes of 0.1, 0.01, and 0.002 m. Note that the addition of very small amplitude waves significantly alters the irradiance pattern.

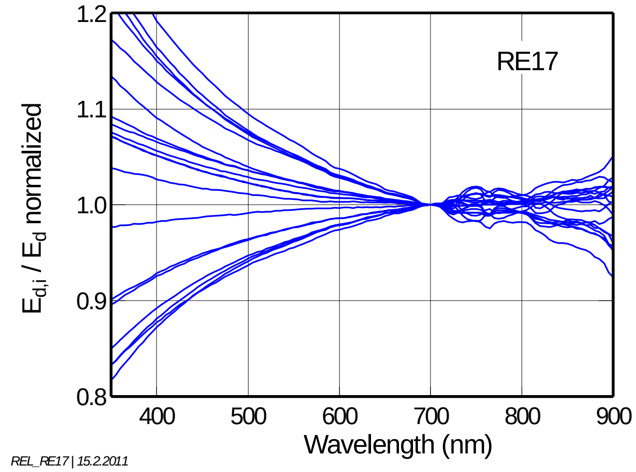
Zanefeld et al. (2001): Influence of surface waves on measured and modeled irradiance profiles. *Applied Optics* **40**, 1442-1449.

Very complete book on the topic:
R. E. Walker, Marine Light Field Statistics (Wiley, 1994)

- Wave focusing induces large fluctuations
- Statistics is well known
- **Wavelength dependency?**
- **Other sources of variability?**

Wavelength dependency of E_d variability (Type 1)

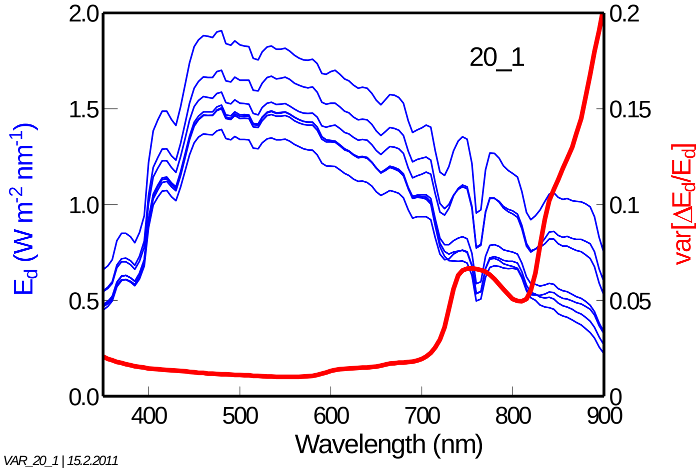


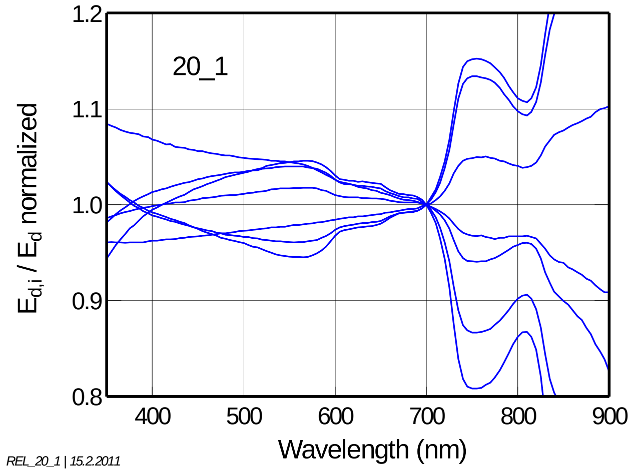


- Smooth spectral shape across VIS
  - no spectral fine structures from E_d
  - power law
- Relevance in our data set
  - γ_{VIS} average = 5.4 %
  - little depth dependency

$$\gamma_{VIS,i} = \frac{E_{d,i}(400)}{E_d(400)} - \frac{E_{d,i}(700)}{E_d(700)}$$

Wavelength dependency of E_d variability (Type 2)





- Characteristic feature in NIR
  - dominated by water absorption
- Relevance in our data set
  - 0–1 m: γ_{NIR} average = 5.7 %
  - > 1 m: γ_{NIR} average = 3.7 %

$$\gamma_{NIR,i} = \frac{E_{d,i}(755)}{E_d(755)} - \frac{E_{d,i}(700)}{E_d(700)}$$

Irradiance model

Irradiance is sum of a direct and a diffuse component

$$E_d(\lambda,z) = f_{dd}E_{dd}(\lambda,z) + f_{ds}E_{ds}(\lambda,z)$$

E_d: downwelling irradiance

E_{dd}, E_{ds}: direct / diffuse component of E_d

f_{dd}, f_{ds}: actual fraction of E_{dd}, E_{ds}

Wave focusing changes f_{dd} and f_{ds}

Depth dependency of each component according to Lambert-Beer law

$$E_{dd}(\lambda,z) = E_{dd}(\lambda,0\text{-})\ \exp\{-[a(\lambda)+b_b(\lambda)]z/\cos\theta_{sun,w}\}$$

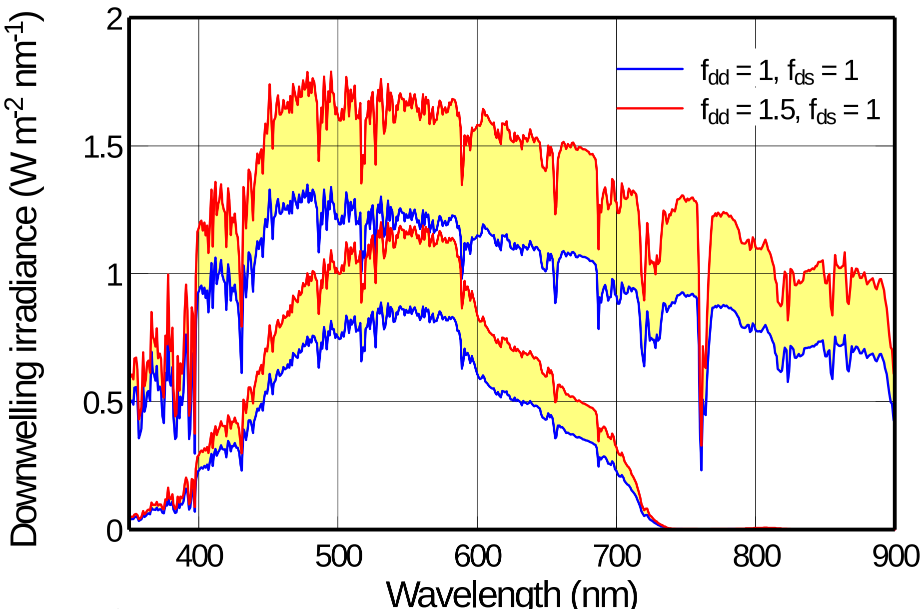
$$E_{ds}(\lambda,z) = E_{ds}(\lambda,0\text{-})\ \exp\{-[a(\lambda)+b_b(\lambda)]z l_{ds}\}$$

l_{ds}: average path length of diffuse radiation.

z: water column thickness above sensor.

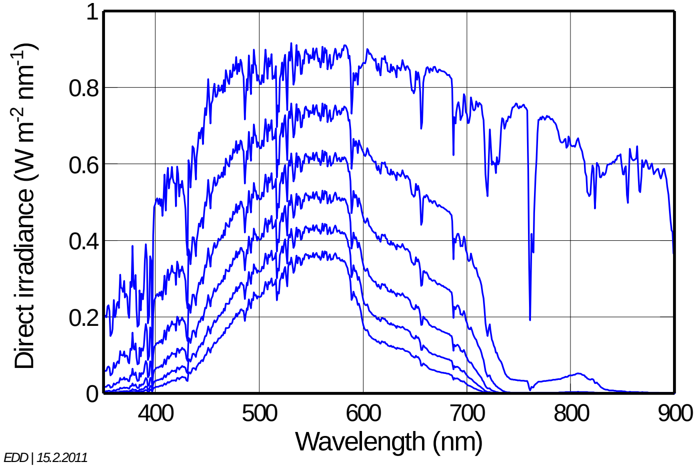
Waves alter z.

Illustration of irradiance model



ED_FDD1_FDS1 | 15.2.2011

Depth dependency: z = 0..5 m



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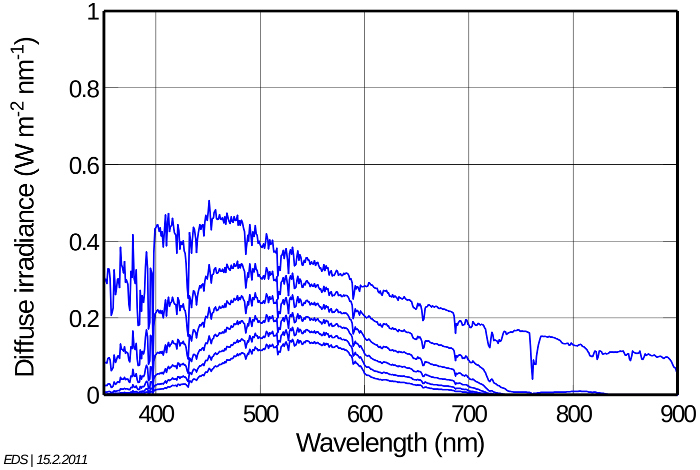


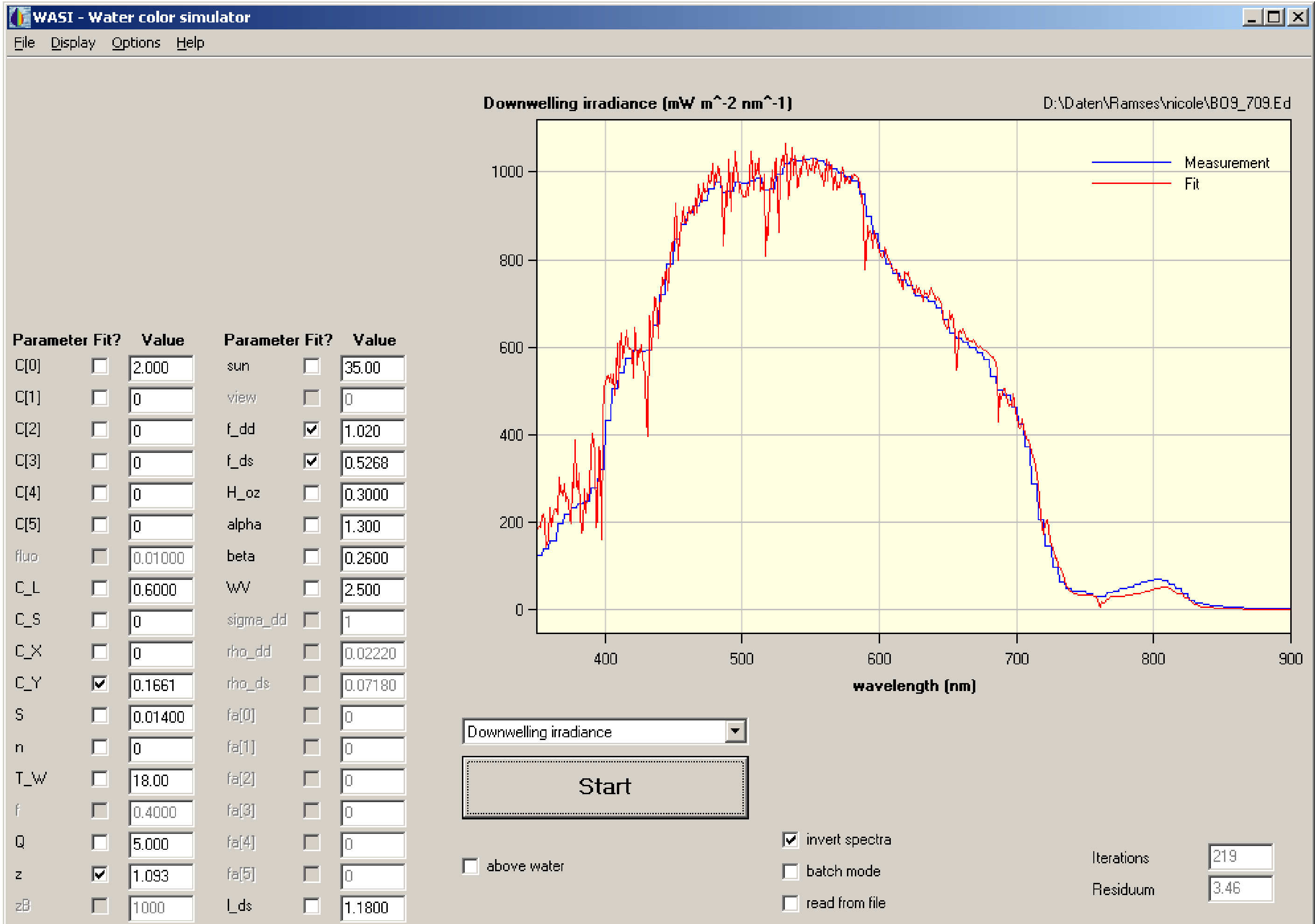
EDS | 15.2.2011

$$E_d(\lambda,z) = f_{dd}E_{dd}(\lambda,z)+ f_{ds}E_{ds}(\lambda,z)$$

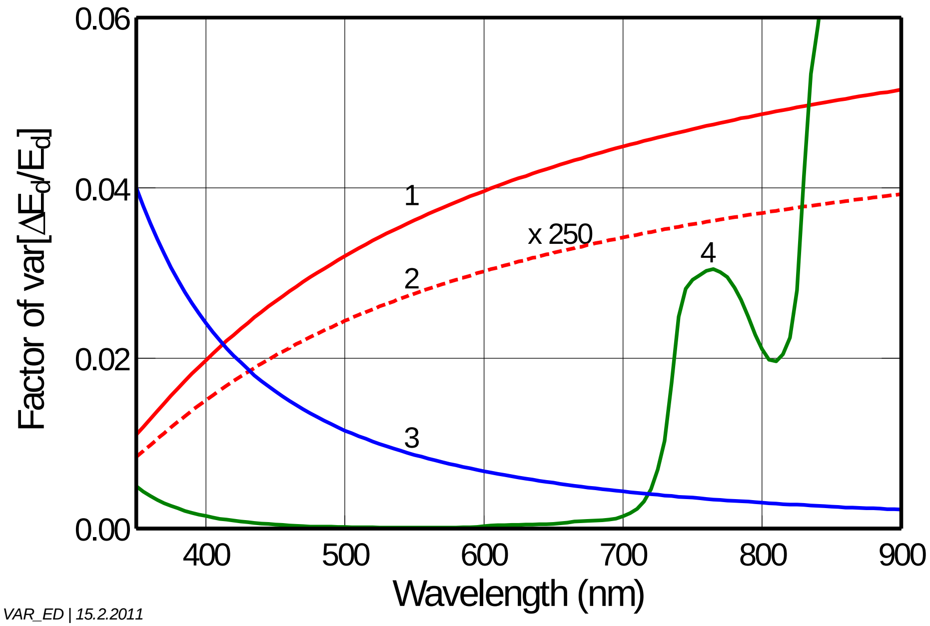
Inversion of irradiance measurements

WASI
software

[ftp.dfd.dlr.de/
pub/wasi](ftp.dfd.dlr.de/pub/wasi)



Sources of irradiance variance (from model)

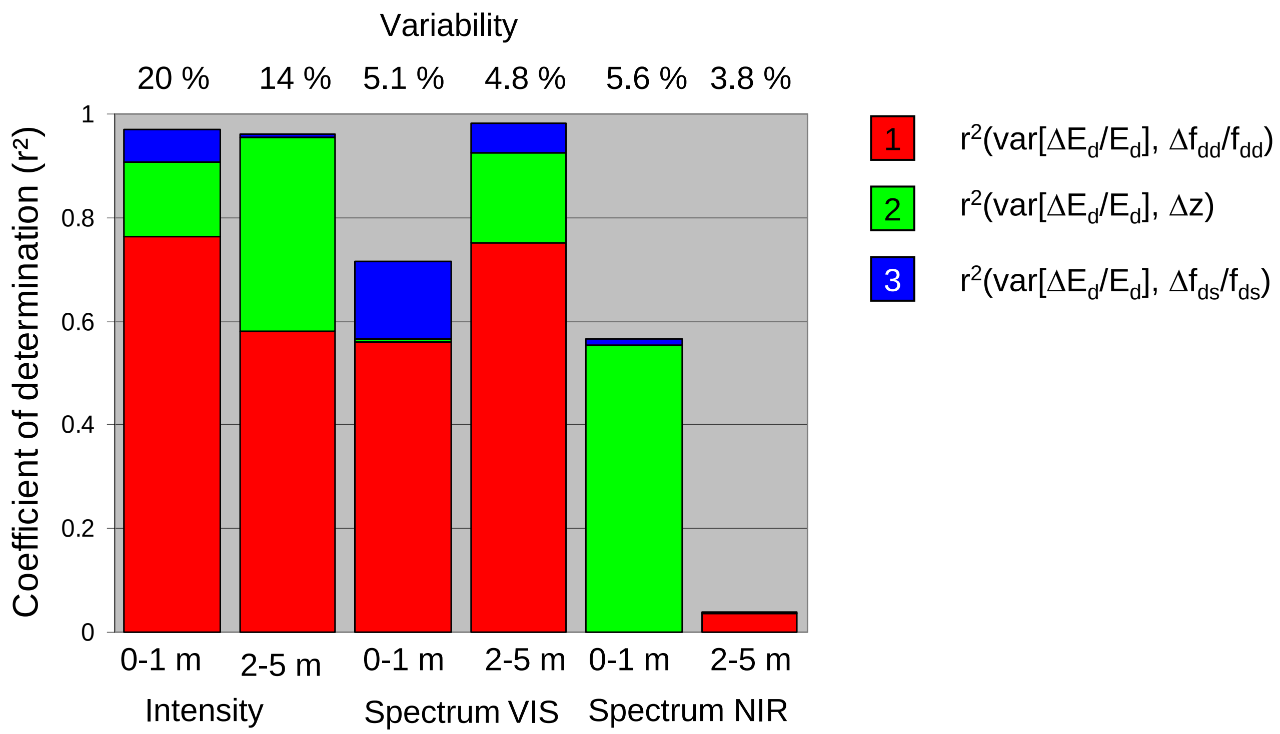


1. Changes of direct radiation due to waves
2. ~~Changes of direct radiation due to sensor tilt~~
3. Changes of diffuse radiation due to waves
4. Changes of sensor depth due to waves and swaying boat

1 | 2 | 3 | 4

$$\mathrm{var}\left[\frac{\Delta E_d(\lambda,z)}{E_d(\lambda,z)}\right] = \underbrace{\left[\frac{r_d(\lambda,z)}{r_d(\lambda,z)+1}\right]^2 \mathrm{var}\left[\frac{\Delta f_{dd}}{f_{dd}}\right]}_{1} + \underbrace{\left[\frac{r_d(\lambda,z)}{r_d(\lambda,z)+1}\right]^2 \tan^2(\theta'_{sun}+\theta_s)\,\mathrm{var}[\theta_s]}_{2} + \underbrace{\left[\frac{1}{r_d(\lambda,z)+1}\right]^2 \mathrm{var}\left[\frac{\Delta f_{ds}}{f_{ds}}\right]}_{3} + \underbrace{\left[\frac{1}{r_d(\lambda,z)+1}\right]^2 [a(\lambda)+b_b(\lambda)]^2 \left[\frac{r_d(\lambda,z)}{\cos\theta'_{sun}}+l_{ds}\right]^2 \mathrm{var}[z]}_{4}$$

Importance of sources



1: Changes of direct radiation due to waves

2: Changes of sensor depth due to waves and swaying boat

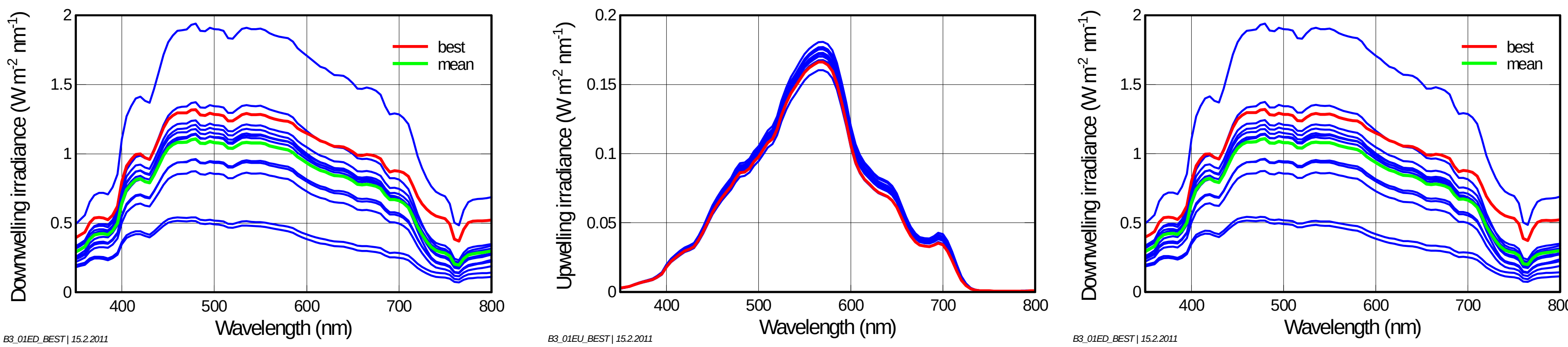
3: Changes of diffuse radiation due to waves

Summary and conclusion

3 relevant sources of irradiance variability (intensity and spectral shape)

- Rank 1: Changes of direct radiation due to waves. var $E_d \sim [r_d/(r_d+1)]^2$. Typical: ± 5 % across VIS.
- Rank 2: Changes of sensor depth due to waves and swaying boat. var $E_d = f(r_d, a, b_b, \theta_{sun}, I_{ds})$. Typical: ± 6 % across NIR.
- Rank 3: Changes of diffuse radiation due to waves. var $E_d \sim [1/(r_d+1)]^2$

$f_{dd} = 0.86$, $f_{ds} = 0.94$



Assignment of „best“ in-water measurement requires above-water measurement in order to determine the actual values f_{dd}, f_{ds}.

P. Gege, N. Pinnel (2011): Sources of variance of downwelling irradiance in water. *Applied Optics (in press).*