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Combined impact of illumination effects and reflectance anisotropy on high resolution imaging spectroscopy data and derived vegetation products

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Introduction

The complex radiative transfer (RT) in coupled atmosphere-vegetation-systems requires accurate analytical solutions to reliably extract vegetation variables from spatial high resolution imaging spectroscopy (IS) data.

Illumination effects, i.e., changing surface irradiance (*E*) including their direct (E^{dir}) and diffuse (E^{dif}) components, were found to largely impact the retrieval accuracy of vegetation variables from IS data [1].

We quantify the sensitivity of IS data, retrieved reflectances and vegetation variables to inaccurate assumptions of E^{dir} and E^{dif}. We use experimental and simulated data and focus on the NDVI, the PRI, and chlorophyll fluorescence (Fs).

Experimental and simulated data

Experimental data

APEX (Airborne Prism EXperiment) [2] data acquired on 26 June 2010 (15:30 UTC) and 29 June 2010 (10:00 UTC) were used to demonstrate the relevance of illumination effects. Data pre-processing included a geo-rectification using PARGE, and a compensation of atmospheric effects using ATCOR-4.

Simulated data

Coupled surface-atmosphere modelling considering the 4-stream theory [3] and using the RT models SCOPE [4] and MODTRAN5 was applied to simulate E^{dir}, E^{dif}, and canopy leaving radiance L_{ToC}:

$$E^{dir} = \tau_{ss} E^0 \cos\theta_{il}$$

$$E^{dif} = \frac{\tau_{sd}+\tau_{ss}\overline{r_{sd}}\rho_{dd}}{1-\overline{r_{dd}}\rho_{dd}} E^0 \cos\theta_{il}$$

$$L_{ToC} = \frac{r_{so}\cdot E^{dir}+r_{do}\cdot E_t^{dif}}{\pi}$$

E^{dir}	direct irradiance
E^{dif}	diffuse irradiance
E^0	extraterrestrial solar irradiance
L_{ToC}	top-of-canopy radiance reflected by the surface
θ_{il}	illumination zenith angle
τ_{ss}	direct transmittance of the atmosphere for sunlight
τ_{sd}	diffuse transmittance of the atmosphere for sunlight
ρ_{dd}	spherical albedo
r_{sd}	directional-hemispherical reflectance (DHR) of the surroundings
r_{dd}	bi-hemispherical reflectance (BHR) of the surroundings
r_{so}	bi-directional reflectance factor (BRF) of the target
r_{do}	hemispheric-directional reflectance factor (HDRF) of the target

Eight homogeneous canopies observed under 13 atmospheres and six representations of E^{dir} (varied between 0-100%, E^{dif} remeined untouched) were analyzed.

Vegetation variables

Three vegetation variables were investigated, the NDVI as proxy for vegetation health and structure, PRI as indicative variable for the current de-epoxidation state of xanthophylls, and Fs as direct indicator of the state of instantaneous plant photosynthesis.

The vegetation variables were calculated considering true (*tR*) and apparent reflectance (*aR*). *tR* is defined as ratio of simulated L_{ToC} and known surface *E*. *aR* is defined as s ratio of simulated L_{ToC} and wrong assumptions on surface *E*, i.e., E^{dir} was always set to 100%.

Vegetation indices

$$NDVI = \frac{(R_{800}-R_{640})}{(R_{800}+R_{640})};\ PRI = \frac{(R_{531}-R_{570})}{(R_{531}+R_{570})}$$

Chlorophyll fluorescence

$$\begin{cases} L_i = L_i^p + \frac{1}{\pi}\frac{\left[\left(E_i^{dir}+E_i^{dif}\right)R_i+Fs_i\right]\tau_{oo}^i}{1-R_i\rho_{dd}^i} \\ L_o = L_o^p + \frac{1}{\pi}\frac{\left[\left(E_o^{dir}+E_o^{dif}\right)R_o+Fs_o\right]\tau_{oo}^o}{1-R_o\rho_{dd}^o} \end{cases} \qquad X_j = \frac{\left(L_j-L_j^p\right)}{\tau_{oo}^j}, \quad j=i,o \qquad E_j = \frac{1}{\pi}\left[E_j^{dir}+E_j^{dif}\right], \quad j=i,o$$

$$Fs = B\left[\frac{X_i\left(E_o+X_o\cdot\rho_{dd}^o\right)-AX_o\left(E_i+X_i\cdot\rho_{dd}^i\right)}{B\left(E_o+X_o\cdot\rho_{dd}^o\right)-A\left(E_i+X_i\cdot\rho_{dd}^i\right)}\right] \qquad \left.\begin{matrix} R_i = AR_o \\ Fs_i = BFs_o \end{matrix}\right\}$$

$NDVI$	normalized difference vegetation index
PRI	photochemical reflection index
Fs	fluorescence
R	ToC reflectance
L	at-sensor radiance
L^p	path scattered radiance
τ_{oo}	total transmittance in viewing direction
A	factor relating reflectance in- and outside of an absorption band
B	factor relating fluorescence in- and outside of an absorption band
i	wavelength within (i) an absorption band
o	wavelength outside (i) of an absorption band

Results

Illumination effects in IS data

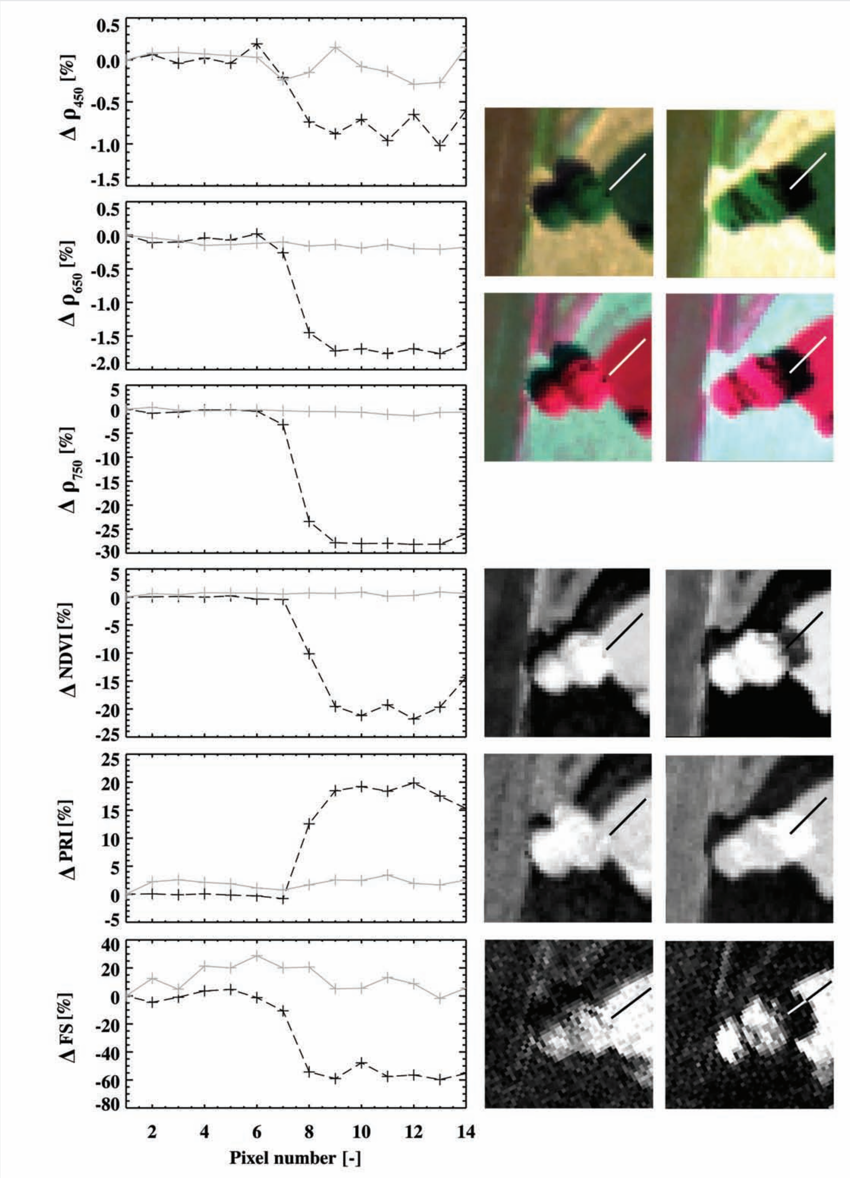

Figure 1: Spatial gradient of illumination effects in HCRF data and vegetation variables in a partly shaded meadow. From top to bottom: APEX-HCRF true colour composite, APEX-HCRF false colour composite, NDVI, PRI, Fs. Grey line: HCRF data and vegetation variables in a fully illuminated meadow; black line: HCRF data and vegetation variables of the same but partly shaded meadow. The corresponding maps are shown on the right.

Total surface irradiance

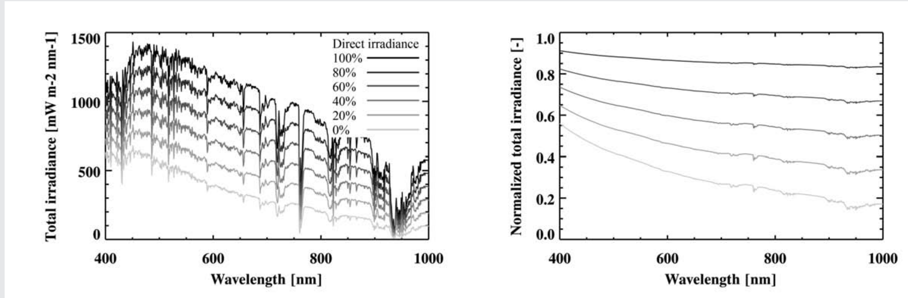

Figure 2: Total *E* as function of changing E^{dif}/E^{dir} fluxes. E^{dir} was changed in 20% steps. Left: Total *E*. Right: Normalized total *E* considering the 100% E^{dir} case as reference.

Apparent surface reflectance

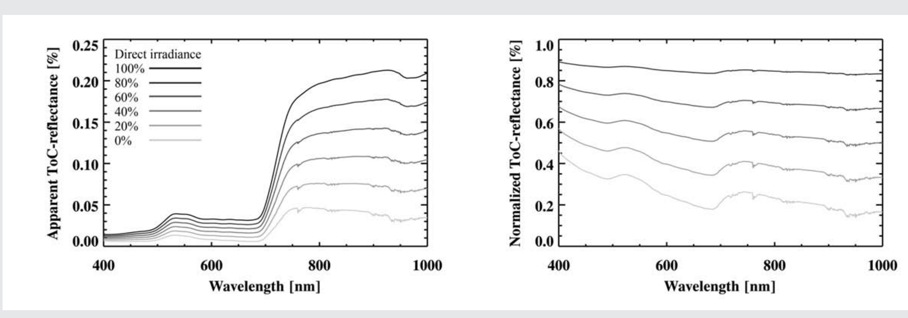

Figure 3: Apparent ToC bidirectional reflectance factor (BRF) as function of changing E^{dif}/E^{dir} fluxes. E^{dir} was changed in 20% steps. Left: Apparent ToC-BRF. Right: Normalized apparent ToC-BRF considering the 100% E^{dir} case as reference.

Impact of illumination effects on IS vegetation variables

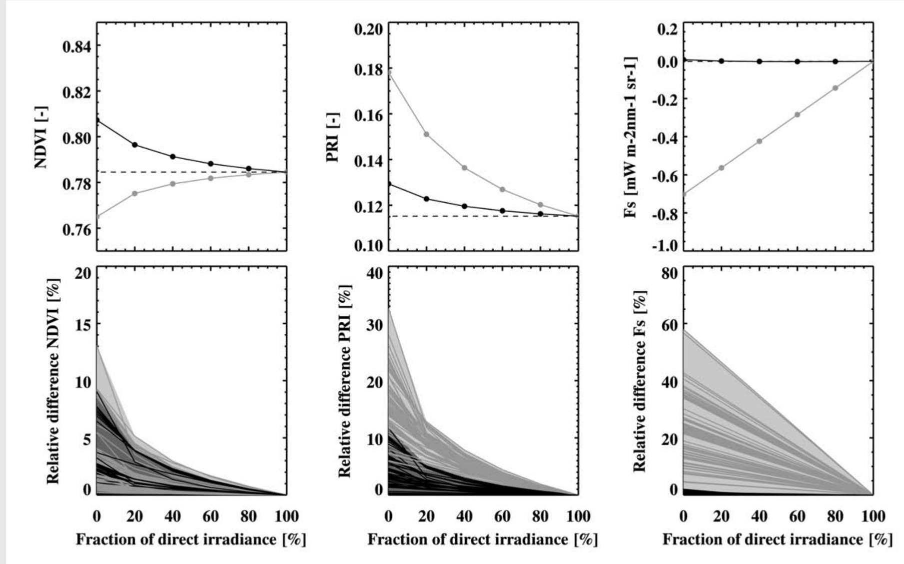

Figure 4: Vegetation variables in response to changing surface *E*. Top panels: Average variable responses of all test cases. Bottom: Individual variable responses. Black: true variable values. Grey: apparent variable values.

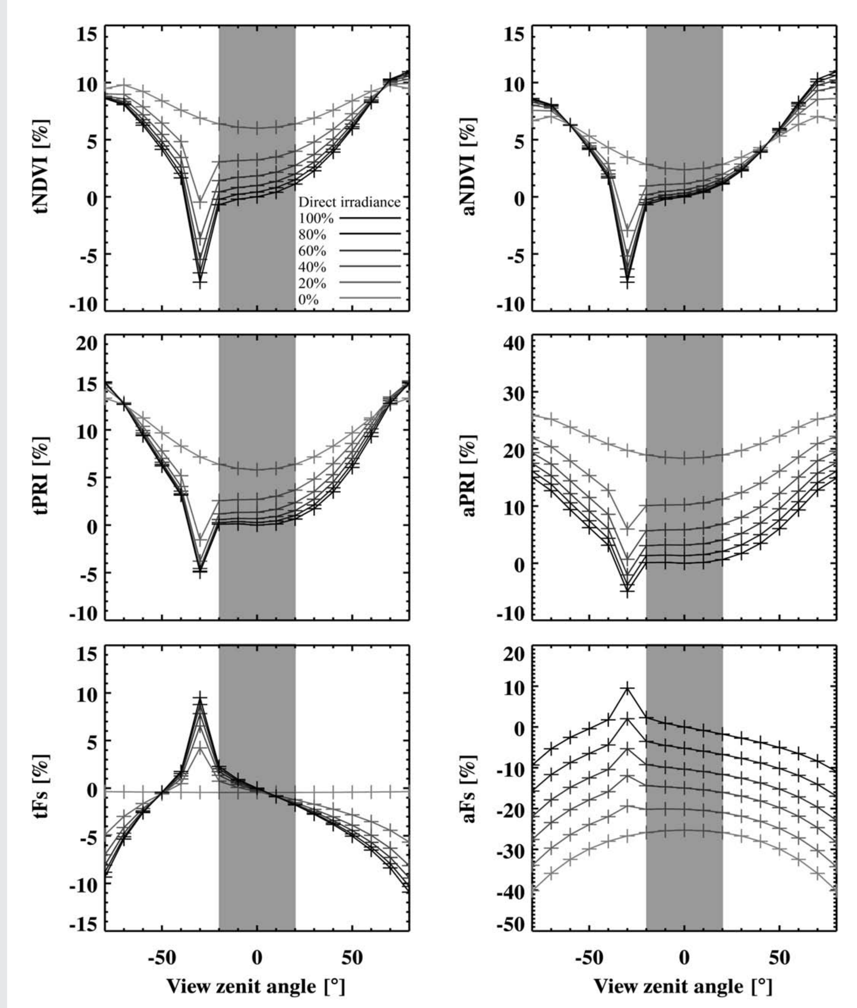

Figure 5: Angularity of vegetation variables. Left: Variable variation considering correct fractions of E^{dir} and E^{dif}. Right: The same analysis but assuming always 100% E^{dir}. Properties of the shown example: *canopy:* dense vegetation, Chl=40 µg cm^{-2}, LAI=2.0, LIDF=spherical, *atmosphere*: VIS=20, aerosol model=mid-latitude summer, sun zenith=0°.

Conclusions

- Reflectance anisotropy causes a dependency of vegetation variables to changing surface *E*
- Canopy specific sensitivities of reflectance based vegetation variables for changing surface *E* is an intrinsic property of vegetation surfaces (NDVI 9%, PRI 13%), but a retrieval artefact for FS (2%)
- Wrong assumptions on surface *E* causes uncertainties in retrieved vegetation variables (NDVI 13%, PRI 32%, and Fs 58%)
- ToA retrieval approaches describing the RT in complex atmosphere-surface systems as a complete and realistic physical process are suggested for quantitative vegetation analysis

[1] Damm, A. et al. (submitted to RSE). "Impact of changing fractions of direct and diffuse irradiance on high resolution imaging spectroscopy data and derived vegetation variables."
[2] Jehle, M., Hueni, A., Damm, A., D'Odorico, P., Kneubühler, M., Meuleman, K., Schlapfer, D., Schaepman, M.E., & Weyermann, J. (2010). APEX - current status, performance and validation concept. IEEE Sensors 2010 Conference, 533-537.
[3] Verhoef, W. & Bach, H. (2007). "Coupled soil-leaf-canopy and atmosphere radiative transfer modeling to simulate hyperspectral multi-angular surface reflectance and TOA radiance data.", Remote Sensing of Environment, vol. 109, pp. 166-182.
[4] Van der Tol, C., Verhoef, W., Timmermans, A., Verhoef, A., & Su, Z. (2009). An integrated model of soil-canopy spectral radiances, photosynthesis, fluorescence, temperature and energy balance. Biogeosciences, 6, 3109-312.

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