# USE SPECTRAL DERIVATIVES FOR ESTIMATING CANOPY WATER CONTENT

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**ABSTRACT:**

Hyperspectral remote sensing has demonstrated great potential for accurate retrieval of canopy water content (CWC). This CWC is defined by the product of the leaf equivalent water thickness (EWT) and the leaf area index (LAI). In this paper the spectral information provided by the canopy water absorption feature at 970 nm for estimating and predicting CWC was studied using a modelling approach and in situ spectroradiometric measurements. The relationship of the first derivative at the right slope of the 970 nm water absorption feature with CWC was investigated with the PROSAIL radiative transfer model at a 1 nm sampling interval and tested for field spectroradiometer measurements obtained at an extensively grazed fen meadow as test site.
PROSAIL simulations (using coupled SAIL/PROSPECT-5 models) showed a linear relationship between the first derivative over the 1015 – 1050 nm spectral interval and CWC ($R^2$ = 0.97), which was not sensitive for leaf and canopy structure, soil brightness and illumination and observation geometry. For 40 plots at the fen meadow ASD FieldSpec spectral measurements yielded an $R^2$ of 0.68 for the derivative over the 1015 – 1050 nm interval with CWC. This relationship appeared to match the simulated relationship obtained from the PROSAIL model. It showed that one may transfer simulated results to real measurements obtained in the field, thus giving them a physical basis and more general applicability. Consistency of the results confirmed the potential of using simulation results for calibrating the relationship between this first derivative and CWC.
Another advantage of using the derivative at the right slope of the 970 nm absorption feature is its distance from the atmospheric water vapour absorption feature at 940 nm. If one cannot correct well for the effects of atmospheric water vapour, the derivative at the right slope is preferred over the one at the left slope.

## 1. INTRODUCTION

Biogeochemical processes, such as photosynthesis, evaporation and net primary production, are directly related to foliar water (Running and Gower, 1991; Running and Nemani, 1991). Thus, canopy water content is an important variable for mapping and monitoring the condition of the terrestrial ecosystem.

In this paper, we focus on retrieving canopy water content from optical remote sensing data, in particular hyperspectral data. Remote sensing techniques provide an integrated signal over the spatial resolution element of the detector. As a result, the canopy water content, being the amount of water per unit ground area, is a variable of interest. However, in radiative transfer (RT) models often the amount of water per unit leaf area, the so-called equivalent water thickness (EWT), is used (Hunt Jr. and Rock, 1989; Jacquemoud and Baret, 1990). By multiplying the EWT with the leaf area per unit ground area (called the leaf area index, LAI) we get the canopy water content (CWC in kg.m$^{-2}$):

$$CWC = LAI \times EWT \tag{1}$$

Another way of calculating CWC is by taking the difference between fresh weight (FW in kg.m$^{-2}$) and dry weight (DW in kg.m$^{-2}$):

$$CWC = FW - DW \tag{2}$$

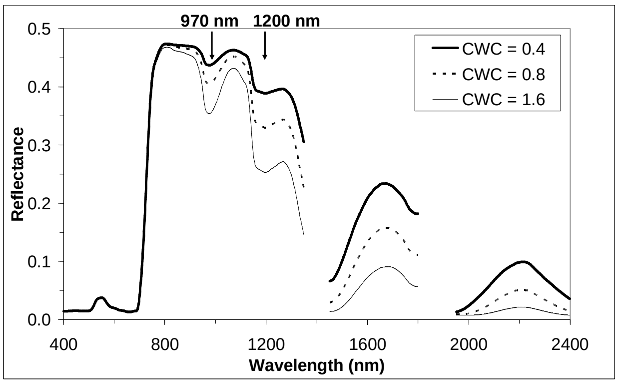


Figure 1. Example of three canopy spectral signatures as simulated with PROSAIL for different CWC values (in kg.m$^{-2}$), showing the position of the 970 nm and 1200 nm absorption features.

Figure 1 shows an example of RT simulation results (using PROSAIL, see section 2.1) for a vegetation spectrum with three different CWC values. No simulation results are shown for the major atmospheric water absorption features around 1400 nm and 1900 nm, because these absorptions are such that hardly any solar radiation reaches the Earth's surface at these wavelengths. As a result, these are not used in remote sensing of land surfaces. Figure 1 shows that CWC in particular has an effect in the near-infrared (NIR) and the shortwave-infrared

(SWIR) part of the spectrum. Figure 1 also shows two water absorption features at approximately 970 nm and 1200 nm that are caused by the absorption by O–H bonds in liquid canopy water (Curran, 1989). Accurate measurements at these absorption features in the NIR are feasible with the increasing availability of hyperspectral images (Schaepman et al., 2009).

Danson et al. (1992) showed that the first derivative of the reflectance spectrum corresponding to the slopes of the absorption features provides better correlations with leaf water content than those obtained from the direct correlation with reflectance. Rollin and Milton (1998) found moderate correlations between the first derivative at the left slope of both absorption features and CWC for a grassland site in the UK. Clevers et al. (2008) applied derivatives in a preliminary study at the field and airborne level. These studies showed that spectral derivatives at the slopes of the 970 nm and (to a lesser extent) 1200 nm absorption feature have good potential as predictors of CWC.

Recently, Clevers et al. (2010) showed that the first derivative of the reflectance spectrum at wavelengths corresponding to the left slope of the minor water absorption band at 970 nm was highly correlated with CWC. PROSAIL model simulations showed that it was insensitive to differences in leaf and canopy structure, soil background and illumination and observation geometry. However, these wavelengths are located close to a water vapour absorption band at about 940 nm (Gao and Goetz, 1990). In order to avoid interference with absorption by atmospheric water vapour, the potential of estimating CWC using the first derivative at the right slope of the 970 nm absorption feature is studied in this paper for a dataset acquired in 2008. Results are compared with PROSAIL simulations, using a new version of the PROSPECT model (Feret et al., 2008).

## 2. MATERIAL AND METHODS

### 2.1 PROSAIL Radiative Transfer Model

PROSAIL is a combination of the PROSPECT leaf RT model (Jacquemoud and Baret, 1990) and the SAIL canopy RT model (Verhoef, 1984), which has been used extensively over the past few years for a variety of applications (Jacquemoud et al., 2009). At the leaf level, PROSAIL is using leaf chlorophyll content ($C_{ab}$), equivalent leaf water thickness (EWT), leaf structure parameter (*N*) and leaf dry matter ($C_m$) as inputs. At the canopy level, input parameters are LAI, leaf inclination angle distribution, soil brightness, ratio diffuse/direct irradiation, solar zenith angle, view zenith angle and sun-view azimuth angle. It also includes a parameter describing the hot-spot effect (Kuusk, 1991). In a previous study, we used an older version of PROSPECT (version 3) simulating leaf reflectance and transmittance at a 5 nm spectral sampling interval. Recently, version 5 of PROSPECT has been released, performing simulations at a 1 nm spectral sampling interval and using updated values for the specific absorption coefficients of leaf constituents (Feret et al., 2008).

To study the relationship between derivatives and CWC (calculated from LAI and EWT), the effects of the main leaf and plant inputs on this relationship were studied. $C_{ab}$ could be kept constant since it does not exhibit any effect beyond 800 nm. Since the specific absorption coefficient for dry matter is quite low and constant below 1300 nm (Fourty et al., 1996), a constant value for $C_m$ was used according to the findings of Jung et al. (2009) for a floodplain meadow. At the canopy level, the actual observation and solar angles of the experimental measurements (section 2.3) were used. Also spectral soil brightness values were obtained from the actual experiments. The other inputs for the PROSAIL simulations were varied according to the values given in Table 1.

Since the absorption features of leaf constituents are implemented in the PROSAIL model by means of look-up tables and not as continuous functions, simulated spectra have to be smoothed for calculating derivatives. The simulated spectra were smoothed using an 8 nm wide moving Savitsky-Golay filter applying a fourth-degree polynomial fit within the window according to the results of Le Maire et al. (2004).

Table 1. Nominal values and range of parameters used for the canopy simulations with the PROSAIL model.

| PROSAIL parameters | Nominal values and range |
|---|---|
| Equivalent water thickness (EWT) | 0.01 – 0.10 $g.cm^{-2}$ (step of 0.01) |
| Leaf dry matter ($C_m$) | 0.002 $g.cm^{-2}$ † |
| Leaf structure parameter (*N*) | 1.0 / 1.8 / 2.5 |
| Chlorophyll concentration ($C_{ab}$) | 40 $\mu g.cm^{-2}$ |
| Leaf area index | 0.5/ 1.0 / 1.5 / 2 / 3 / 4 / 5 / 6 |
| Leaf angle distribution | Spherical / Planophile / Erectophile |
| Hot-spot parameter | 0.0 / 0.1 |
| Soil reflectance | Actual values |
| Diffuse/direct radiation | 0 |
| Solar zenith angle | 35° |
| View zenith angle | 0° |
| Sun-view azimuth angle | 0° |

†Source: (Jung et al., 2009)

### 2.2 Study Site

The study site is an extensively grazed fen meadow acting as a buffer zone around a protected bog ecosystem, located in the Achterhoek area in the Netherlands and forming part of Europe's Natura-2000 ecological network. Ground sampling took place from June 9th – 11th, 2008. 40 Plots of 3 by 3 m were randomly distributed over the site. In three corners of each plot subplots of 0.5 x 0.5 m were harvested by cutting all above-ground vegetation. Vegetation fresh weight for every subplot was determined after harvesting. After drying for 24 hours at 70°C, vegetation dry weight and CWC were determined. Subsequently, the average CWC per plot was calculated.

### 2.3 Field Spectroradiometry

The study site was measured with an ASD FieldSpec Pro FR spectroradiometer on June 9th and 10th, 2008. Nadir measurements were performed between 11h and 15h local time, resulting in a solar zenith angle varying between 30º and 40º. All subplots of all 40 plots were measured before harvesting the biomass. Measurement height above the plot was about 1.5 m and the instrument field of view was 25°. As a result, at the plot level a circular area of about 0.35 $m^2$ was measured and each measurement represents the average of 50 readings at the same spot. The sampling interval was 1 nm. Calibration was done by using a Spectralon white reference panel.

After calculating average spectra per plot, the resulting spectra were smoothed using a 15 nm wide moving Savitsky-Golay filter (applying a second order polynomial fit within the window) to reduce instrument noise.

## 3. RESULTS AND DISCUSSION

### 3.1 PROSAIL Simulations

The simulation results obtained with the improved PROSAIL model (using PROSPECT-5) using a 1 nm spectral sampling interval showed that for many spectral positions beyond 900 nm the relationship between the first derivative and CWC is statistically significant at $p < 0.001$. In addition to the left slope of the 970 nm water absorption feature, also relationships at the right slope of this feature and at the left slope of the 1200 nm feature are highly significant (Figure 2). In this paper, focus is on the right slope of the 970 nm absorption feature, because there no influence of absorption by atmospheric water vapour is expected. Figure 2 shows that the reflectance at this right slope is increasing gradually and that the coefficient of determination ($R^2$) for the relationship between the first derivative of adjacent wavelengths and CWC is rather constant. Therefore, we may calculate the first derivative over a wider interval, making the choice of wavelengths for derivative calculation less critical and making the derivative calculation more robust. Experimental results later in this paper suggest that an interval between 1015 and 1050 nm is a good choice. Figure 3 provides the relationship between the first derivative over the 1015 – 1050 nm interval and CWC for variations in model input parameters as given in Table 1. There is an offset for the linear regression line because soil reflectance was not constant over the spectral interval. Field measurements at the test site yielded a reflectance of 0.39 at 1015 nm and a reflectance of 0.40 at 1050 nm. Largest scatter around the linear regression line visible in Figure 3 is caused by the variation in leaf inclination angle distribution. In the next section it will be tested whether this simulated relationship matches the one found with experimental data.

### 3.2 Achterhoek Study Site

For the Achterhoek site in total 40 plots were studied. Figure 4 shows the $R^2$-values for the relationship between spectral derivatives and CWC. The $R^2$ for the 1015 – 1050 nm interval again is constant for this test site. It is lower than the best value at the left slope, but the observed $R^2$-values above 0.65 are statistically significant at $p < 0.001$. The $R^2$ at the right slope over the 1015 – 1050 nm interval is 0.68 (Figure 5). The predictive power of the first derivative as index for estimating CWC was assessed by estimating the root mean square error of prediction (RMSEP) using the leave-one-out cross-validation approach. The calculated RMSEP is 0.21 $kg.m^{-2}$ (as relative to an average CWC of 0.53 $kg.m^{-2}$). The relationship is in agreement with the one found for the simulated data from PROSAIL in Figure 3, which are plotted at the background of the Achterhoek results in Figure 5.

The agreement between the experimental data and PROSAIL is good when using reflectance derivatives over the 1015 – 1050 nm interval. Therefore, the relationship between first derivative and CWC was trained with PROSAIL and then this relationship was applied on the experimental data. The calibrated relationship is given in Figure 3. When applying this relationship to the experimental data of the Achterhoek site,

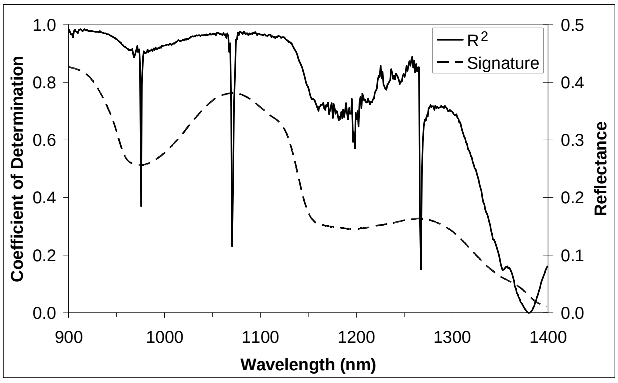


Figure 2. Coefficients of determination between CWC and first derivative of canopy reflectance as simulated by PROSAIL. The dotted line provides an example of a simulated canopy reflectance signature.

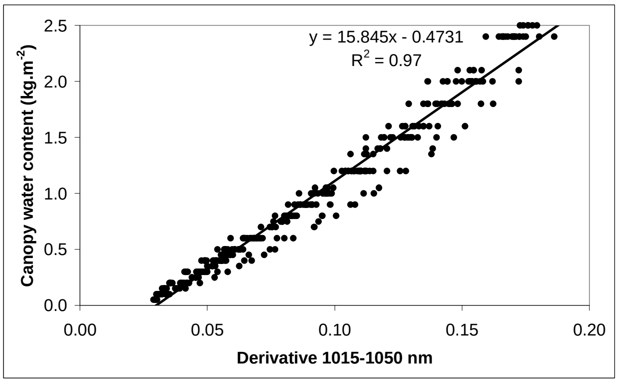


Figure 3. Relationship between first derivative of canopy reflectance over the interval 1015 – 1050 nm and CWC (PROSAIL simulations with varying input parameters according to Table 1).

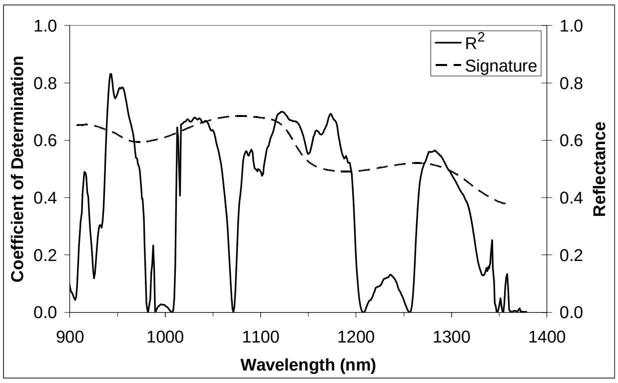


Figure 4. Coefficients of determination between CWC and first derivative of canopy reflectance as measured with the ASD FieldSpec at the Achterhoek site in 2008. The dotted line provides an example of a measured canopy reflectance signature.

Figure 6 illustrates the comparison of the estimated values with those obtained from the ASD FieldSpec measurements. The RMSEP derived from this Figure 6 is 0.25 $kg.m^{-2}$. This value is about equal to the RMSEP value of 0.21 $kg.m^{-2}$ obtained for the experimental data themselves using the leave-one-out method (Figure 5). Figure 6 shows that we get a slight overestimation of CWC in this way.

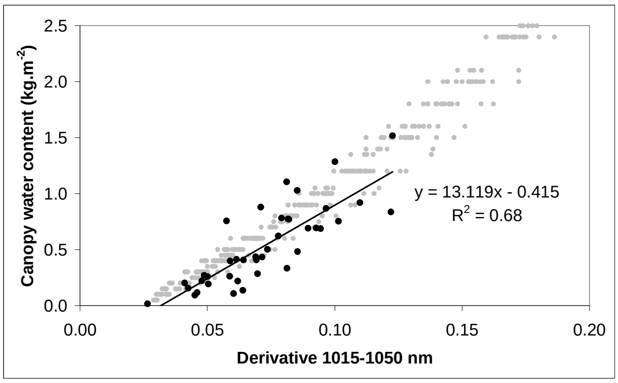


Figure 5. Relationship between first derivative of canopy reflectance over the interval 1015 – 1050 nm and CWC at the Achterhoek site in 2008. At the background the simulated relationship of Figure 3 is shown.

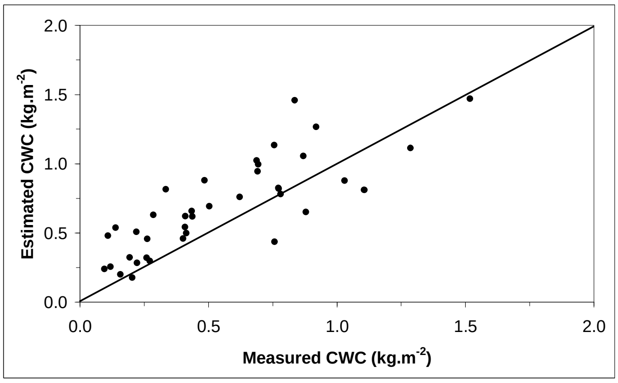


Figure 6. Comparison between CWC measurements from field samples and CWC estimations using PROSAIL simulations of the relationship between CWC and the spectral derivative over the 1015 – 1050 nm interval.

## 4. CONCLUSIONS

Results presented in this paper show that the spectral derivatives for wavelengths on the right slope of the water absorption feature at 970 nm can be used for estimating canopy water content (CWC). PROSAIL model simulations were performed using the improved PROSPECT-5 model as described by Feret et al. (2008). A linear relationship between first derivative over the 1015 – 1050 nm spectral interval and CWC was found, which was not very sensitive for leaf and canopy structure. Field spectroscopic measurements at a fen meadow confirmed the simulation results. The relationship between the first derivative over the 1015 – 1050 nm interval and CWC based on in-situ spectral measurements obtained in the field appeared to match the simulated relationship obtained from the PROSAIL model. This showed that one may transfer simulated results to real measurements obtained in the field, thus giving them a physical basis and more general applicability.

Both simulated spectra and experimental FieldSpec spectra showed that the right slope of the 970 nm absorption feature is linear (constant) in the range from about 1015 nm up to about 1050 nm. Due to this broad interval, the first derivative over this 1015 – 1050 nm interval can be measured more accurately than the derivative at a certain spectral position (or narrow interval). As a result, this derivative also is more robust and less susceptible to noise. Smoothing the spectral measurements did not give better results than non-smoothed measurements. Smoothing was necessary when using narrow intervals (Clevers et al., 2008).

The PROSAIL simulations performed in this study do not include an atmospheric model. When using remote sensing observations from an airborne or spaceborne platform, one should also consider the water vapour absorption by the atmosphere. This occurs, for instance, at 940 nm and 1140 nm (Gao and Goetz, 1990; Iqbal, 1983), thus being shifted to shorter wavelengths as compared to the corresponding liquid water absorption features. This means that the effect of water vapour absorptions in the atmosphere occurs at the left slopes of the water absorption features used for estimating CWC. So, if one cannot correct well for the effects of atmospheric water vapour, it is recommended to use the first derivative, e.g., in the 1015 – 1050 nm interval.

Future work will continue focusing on higher spectral resolution instruments, in particular in the water absorption regions at 970 and 1200 nm. Instruments with a significantly higher spectral resolution would be able to assess separately water molecules in atmosphere and vegetation, allowing correct estimations for both atmospheric water vapour and liquid water in vegetation.

## ACKNOWLEDGEMENTS

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