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REMOTE SENSING

COMSPECT: a compact model for green vegetation reflectance spectra in the 400–900 nm wavelength range

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Abstract. A compact empirical model for approximate description of green vegetation reflectance (GVR) spectra in the visible and near infrared wavelength range from 400 to 900 nm is proposed. The aim is to simplify the development of cyber-physical systems for forestry, agriculture, military, and environmental monitoring where distinguishing of artificial objects from the natural background is needed. Based on hyperspectrally measured spectra and simulations with PROSPECT-D and PROSAIL bio-optical leaf and canopy models, a compact model with only a few setup points at significant wavelength values is stated. After assigning the reference unit value to the chlorophyll-caused 670 nm minimum, only four easily understood tuning parameters will define the overall view of the GVR spectrum. Fermi-Dirac distribution like sigmoid step functions and Gaussian functions are used as building blocks to describe the most important spectrum features: flat or slanted ground level, green apex, red edge step, and infrared plateau. The fitting of the common nine wavelength-related parameters and of the four sample-dependent amplitude parameters was performed on the basis of seven data sets measured by a hyperspectral camera and compact spectrograph. As an application example, assessment of the quality of the military masking colour RAL 6031 is presented. The results obtained show that in the case of maximally compact formulation, a reasonable accuracy can be achieved even if only two parameters characterizing the relative heights of the green apex and the red edge step are used.

Key words: compact empirical model, green vegetation reflectance, hyperspectral observation, military masking colour, natural background model, remote sensing.

1. INTRODUCTION

The optical properties of plant leaves and green vegetation have been studied already for more than 300 years [1]. However, this theme has obtained real importance during the recent decades together with the rise of aerial and satellite monitoring [2]. A noticeable interest has appeared also in the field of military applications due to the improved availability of infrared observation tools [3,4]. A number of books, for example [1,5,6], have been published on the elaborate topic of environmental remote sensing.

Noticeable efforts have been made to develop detailed bio-optical physical models of green flora including heterogeneous layers with different optical properties. Two main model families are the PROSPECT on the leaf level and SAIL on the canopy level [1,7,8].

The model named PROSPECT (leaf optical PROperties SPECTra) for biochemical pigments-based modelling of optical properties of tree leaves appeared in 1990 [9]. Later more elaborate versions PROSPECT-5 [10] and PROSPECT-D [11] were developed. The latter uses seven main input parameters and carefully fitted seven internal reflection–absorption tables for all wavelength values in the 400–2500 nm range with a 1 nm step.

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At the canopy level modelling, the abbreviation SAIL (Scattering by Arbitrary Inclined Leaves) appeared in 1984 [12,13]. The SAIL family models can take into account the ratio of scattered and direct light, the illumination and viewing angles, the view field coverage by leaves, angle variation of the leaves, and the influence of wet and dry soil. The important more advanced versions are SAILH with a hot spot parameter added [14] and numerically optimized 4SAIL [15]. The development of joint leaf and canopy level PROSAIL models started in 1992 [16].

However, in the popular versions of PROSAIL the set of input parameters consists already of seven parameters for the PROSPECT-D part and of nine parameters for the 4SAIL part [17]. This sophisticated model can provide an accurate optical characterization of the natural background in a wide visible and near infrared wavelength range from 400 to 2500 nm for an aerial or a satellite viewer; however, for this notable user experience and a great number of model adjustment runs (as shown below in Section 2) are needed to define reasonable values for all specific input parameters before model application.

The sophisticated physical models seek the maximal accuracy of the description of underlying processes and interconnections and may be used to study the influence of elementary underlying mechanisms. But, as a setback, often the set of input parameters becomes large and non-transparent. Thus detailed physical models are irreplaceable tools in in-depth research, yet in the development of larger multilevel hierarchical systems either a too great number of specific input parameters or computational complexity may create a barrier for the application of those models.

An alternative helpful approach for a designer of cyber-physical systems where a robust approximate description of subsystems is needed may provide compact empirical models that are characterized by a limited number of easy to measure (i.e. empirical) tuning parameters. In particular, the compact model for green vegetation reflectance (GVR) spectra is expected to give a useful tool for developing versatile technical systems in different application fields such as forestry, agriculture, military, and environmental monitoring where the detection or hiding of artificial objects in the presence of a natural background is needed.

In the present paper we offer an approximate compact model COMSPECT of GVR spectra with only a few (minimally two, typically four) easily understandable parameters to describe the GVR spectral signatures in the visible and near infrared wavelength range of 400–900 nm. In contrast to the traditional remote sensing aerial/satellite viewpoint, in the present work we are focusing on the viewpoint of a ground observer with a hyperspectral (HS) camera. The wavelength range of 400–900 nm was selected for the following reasons:

- Availability of a HS camera Resonon Pika-II [18] as the main observation tool.
- Correlation with the sensitivity range of a relatively low cost and increasingly popular silicon-based sensor devices (band gap of Si 1.12 eV sets the red edge of infrared visibility near 1050 nm [19]).
- Avoiding the expansion of the model parameter set for the modelling of water-caused infrared minima at 970 nm and above (see Fig. 1).

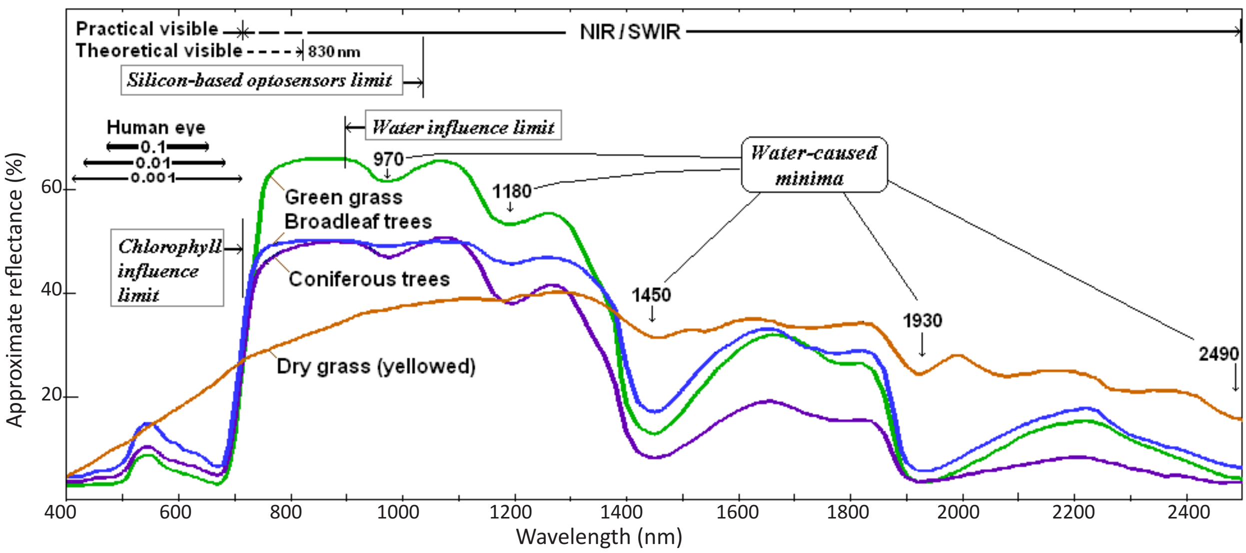

Fig. 1. Typical reflectance spectra of a natural background in the visible and infrared wavelength range of 400–2500 nm. Relative sensitivity ranges of the human eye are shown. High absorption of chlorophyll forms the characteristic 670 nm minimum that is missing from the dry grass curve. The influence of chlorophyll ends at 720 nm, which forms the red edge step. The influence of water causes five characteristic spectral minima at wavelengths above 900 nm.

To construct and test the compact GVR model, we rely on experimental measurements with a HS camera [18] and a compact spectrometer [20] as well as on simulations with the exact models PROSPECT-D and PROSAIL [21].

2. CHARACTERIZATION OF HYPERSPECTRAL SIGNATURES OF THE NATURAL BACKGROUND

The reflectance and transmission spectra of the green vegetation depend on the concentration of light-absorbing compounds (chlorophyll, cellulose, lignin, starch, proteins, etc.) as well as on the reflection and absorption of light by the structural non-homogeneities. Respective relationships have been studied thoroughly by many researchers and have been taken into account in internal parameter tables of PROSPECT and SAIL type models. The typical view of reflectance spectra of a natural background with trees and grass for the visible and near infrared wavelength range of 400–2500 nm is illustrated by Fig. 1.

The dominant factor influencing the GVR in the visible spectrum part in Fig. 1 is the chlorophyll absorbance (with some influence of carotenoids and anthocyanins) near 500 and 670 nm wavelengths, which causes the appearance of the 550 nm green apex and the 700 nm red edge step. In accordance with that, if the leaf aging reduces the chlorophyll content, the characteristic GVR minimum near 670 nm and the sharp red edge 700 nm step will disappear from the spectrum as demonstrated by the dry grass curve in Fig. 1.

The near infrared plateau of 700–1100 nm is a range where biochemical absorption is limited to compounds typically found in dry leaves, mainly cellulose, lignin, and other structural hydrocarbons [22]. The following infrared interval of 1100–2500 nm is mostly affected by green leaf water. Primary water absorbance maxima (reflectance minima) occur at 970, 1180, 1450, 1930, and 2490 nm [23,24].

To support the general observations described in Fig. 1 and to perform a more detailed study of influencing factors at the leaf level, Figs 2 and 3 present a detailed PROSPECT-D and PROSAIL [21] based parameter variation study for the visible and near infrared wavelengths up to 1000 nm. The set of basic 7 + 9 parameter values is described in Table 1.

Figure 2 confirms the following:

- The rather poorly defined parameter of leaf structure, i.e. the number of air–cell walls *N*, has a very strong influence. The effect of higher *N* is similar to reduced chlorophyll concentration. The green apex peak near 550 nm increases almost proportionally to *N* and the red step is shifted towards lower wavelengths by 10–20 nm. The increase of the infrared plateau height at wavelengths over 770 nm is also noticeable but smaller than the increase of the green apex peak.

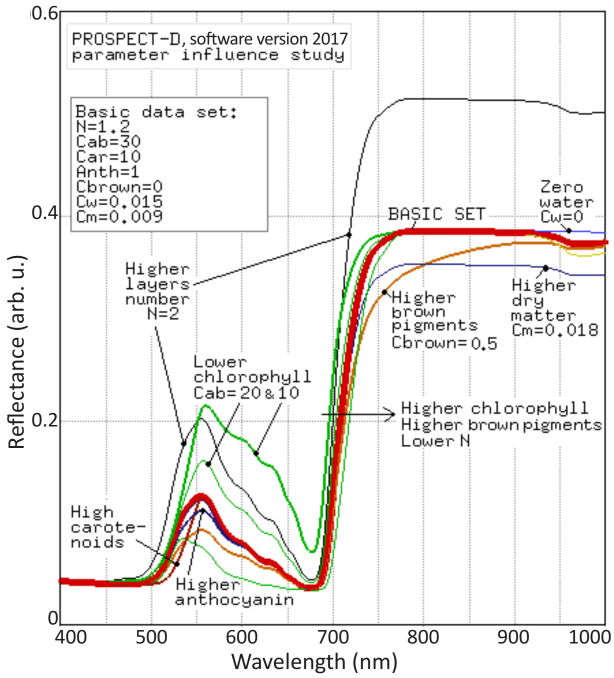

Fig. 2. Study of biophysical factor influences on the green vegetation reflectance spectra with the state-of-the-art leaf level biophysical model PROSPECT-D version 6.0 [21].

- Higher chlorophyll values reduce the height of the green apex and shift the apex wavelength from 550 nm towards 520 nm. The red step wavelength is shifted towards longer wavelengths by 10 nm. Depending on the chlorophyll content, the red step wavelength (defined at the half height) may vary largely between 690 and 720 nm.
- Carotenoids have a limited influence on the green apex's left shoulder between the wavelengths of 510 and 550 nm.
- An increase of anthocyanins (a new parameter in PROSPECT-D compared to the earlier PROSPECT-5) makes the green apex lower but the wavelengths of 620 nm are not influenced.
- A higher brown pigment concentration adds a slope to the infrared plateau and reduces the height of the green apex. In the case of zero brown pigments the infrared plateau has a small negative slope between the wavelengths of 770 and 920 nm.
- The influence of water can be observed only at wavelengths above 930 nm.
- Increased concentrations of dry matter lower somewhat the infrared plateau leaving its slope unchanged.

As the HS camera records the full natural background, to obtain an integral green vegetation view, the leaf level study with PROSPECT-D must be completed with full PROSAIL [21] modelling results for the ground viewer

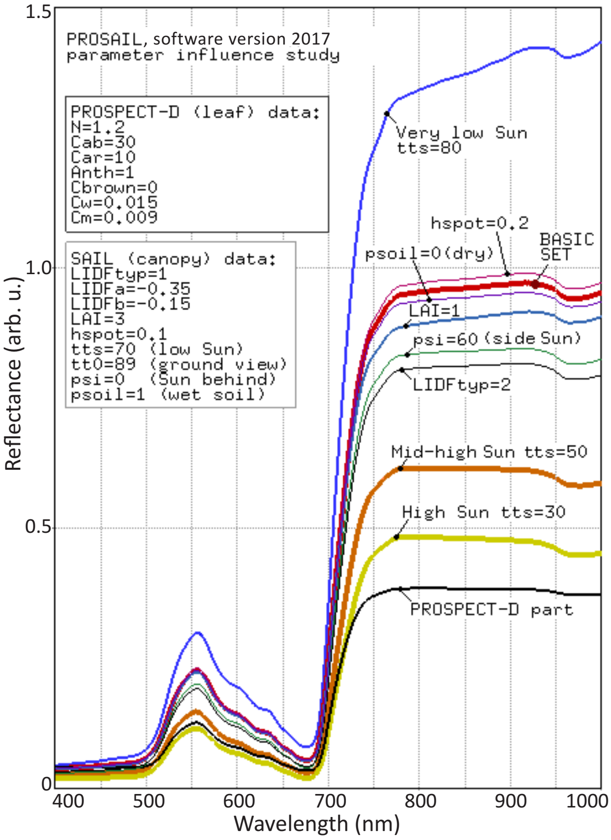

Fig. 3. Additional study of leaf area/inclination and lighting/observation factor influences on the green vegetation reflectance spectra with the state-of-the-art canopy level biophysical model PROSAIL [21].

(zenith angle *tto* close to 90 degrees) with the variation of leaf inclination/density, lighting/observation angles, and the soil wetness parameters. The corresponding parameter variation study is presented in Fig. 3.

Figure 3 demonstrates the following:

- The general view of the leaf level PROSPECT-D curves is maintained for all leaf inclination/density and soil wetness parameter variations.
- However, in the case of the ground viewer and low sunlight close to the horizon the relative heights of the red edge step reached values in the range of 20–30, which are contrary to real observations.
- PROSAIL predicts that the infrared plateau slope is increasing with the near horizon sun lighting.
- The influence of side lighting (relative azimuth angle *psi* different from zero) is small.

The overall conclusion from the results presented in Figs 1–3 is that PROSPECT-D level modelling is rather reliable and the additional effects introduced with PROSAIL are somewhat questionable for the ground viewer. The characteristic wavelengths of minimum and maximum points of GVR spectra curves are not exact constants but may vary by 10–20 nm depending on the concentration of photosensitive pigments. However, the influence of several input parameters is not straightforward and transparent; thus extra expert work for the application of those modelling tools is necessary. This emphasizes the need for an easy-to-use compact model for approximate description of GVR spectra curves.

Table 1. Basic set parameter values for PROSPECT-D and PROSAIL [21] calculations shown in Figs 2 and 3

No.	Symbol	Explanation	Value
PROSPECT-D parameters			
1	*N*	No. of leaf layers	1.2
2	*Cab*	Chlorophyll (*a* + *b*) concentration	30 µg/cm²
3	*Car*	Carotenoids concentration	10 µg/cm²
4	*Anth*	Anthocyanins concentration	1 µg/cm²
5	*Cbrown*	Brown pigments (max = 1)	0
6	*Cw*	Equivalent water thickness	0.015 cm
7	*Cm*	Dry matter concentration	0.009 g/cm²
PROSAIL additional parameters			
1	*LAI*	Leaf Area Index	3 m²/m²
2	*LIDFtyp*	Leaf inclination model type	1
3a	*LIDFa*	Leaf inclination model type 1 parameter *a*	–0.35
3b	*LIDFa*	Leaf inclination model type 2 parameter *a*	30°
4a	*LIDFb*	Leaf inclination model type 1 parameter *b*	–0.15
4b	*LIDFb*	Leaf inclination model type 2 parameter *b*	0
5	*hspot*	Hot spot effect parameter	0.1 m/m
6	*tts*	Sun zenith angle (low Sun)	70°
7	*tto*	Observer zenith angle (ground)	89°
8	*psi*	Sun azimuth angle (behind)	0°
9	*psoil*	Soil wetness parameter (dry = 1)	1

3. IDEA OF A COMPACT GREEN VEGETATION REFLECTANCE MODEL

Reasoning of a compact model that can describe the typical GVR spectral signatures by assigning values only to the four (two) parameters is explained by Fig. 4.

Relying on the form of the typical observed spectra in Fig. 1 and the simulated spectra obtained by the state-of-the-art bio-optical models illustrated in Figs 2 and 3, it is assumed that GVR spectra may be described by a few amplitude values at fixed characteristic wavelengths. If the chlorophyll-caused minimum near 670 nm could be taken as unit value, the number of necessary setup parameters would decrease to four. Additionally, if the blue end value near 420 nm could be made equal to the reference value at 670 nm minimum and the slope of the infrared spectral part between wavelengths 750 and 900 nm could be omitted, only two parameters would be needed for a minimal approximate definition of the compact model. Reasoning for the task statement in relative units is due to the fact that devices such as HS cameras record only the general shape of spectral signatures rather than absolute values of reflected radiation. In fact, the strongest assumption made in the statement of the compact model is the constancy of the characteristic wavelengths. As shown by the simulation results in Figs 2 and 3, the red step and green apex wavelengths may actually shift within a range of 10–20 nm, depending primarily on the chlorophyll and brown pigment ratio and on the rather poorly defined leaf structure parameter N.

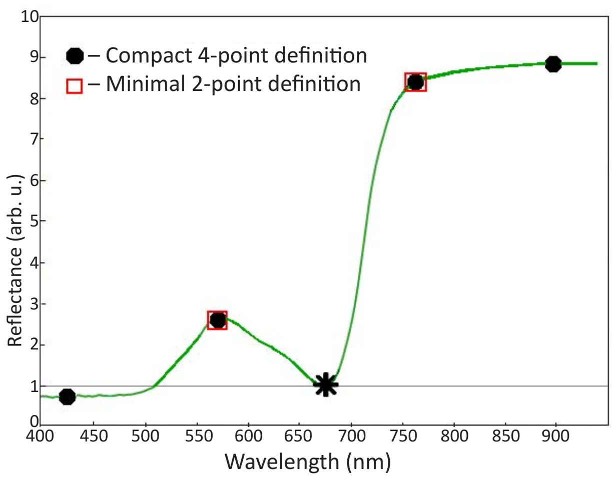

Fig. 4. Idea of approximate compact green vegetation reflectance model for the spectral range 400–900 nm. If the chlorophyll-caused minimum near 670 nm is made equal to unit value, only four adjustment parameters will be needed for an approximate normalized description of spectra registered by HS camera type devices. In a maximally compact robust presentation only two parameters are needed: the relative heights of the green apex and the red edge step. It is assumed that the wavelengths of the characteristic points are approximately constant and the possible small shifts of 10–20 nm due to the variations of photosensitive pigments may be disregarded.

4. COLLECTION OF EXPERIMENTAL DATA

To start the real fitting and testing of a proposed new model, the theoretical predictions should be completed with real experimental data. For that purpose several measurement series were accomplished with two spectroscopic devices: Resonon Pika-II HS camera [18] and Ocean Optics USB-4000 spectrometer [20]. The selected seven data sets are characterized by Table 2 and Fig. 5.

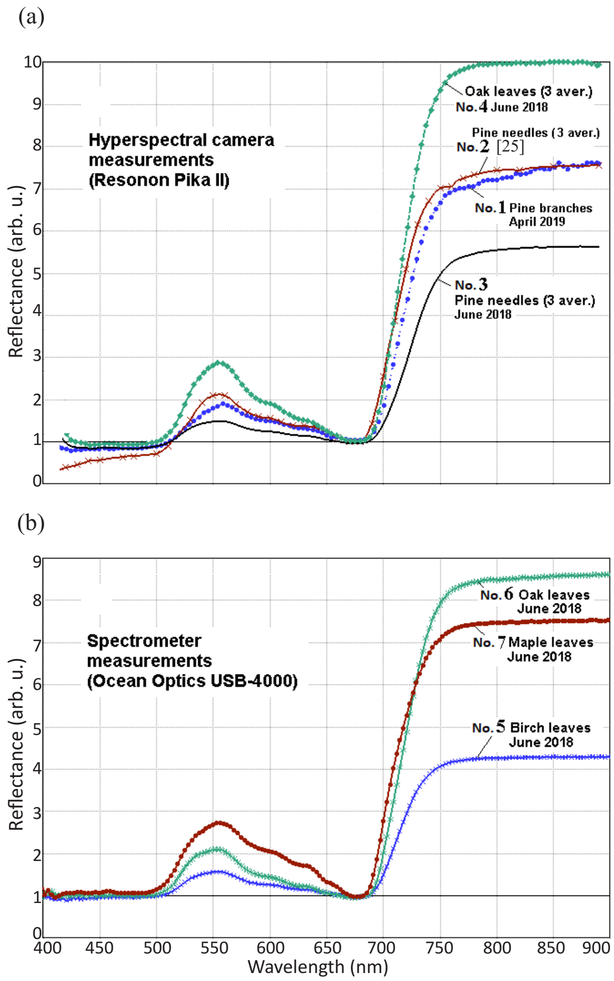

Fig. 5. Collection of seven sets of actual green vegetation reflectance spectra measured by two devices: (a) Resonon hyperspectral camera and (b) Ocean Optics compact spectrometer. The curves are presented in normalized units with respect to the common minimum near the wavelength of 670 nm. The HS camera outdoor calibration was done by standard methodology by using a white test object. The spectrometer results were obtained in laboratory as the ratio of the measured object reflection and the light source (halogen lamp) intensity at measured wavelengths.

Table 2. Characterization of the seven selected data sets for model construction

No.	Data set	Time	Device
1	Pine branches	04.2019	Resonon Pika II HS camera 390–890 nm
2	Pine needles (average of 3, [25, fig. 9]	04.2018	
3	Pine branches (average of 3)	06.2018 field measure-ments	
4	Oak branches (average of 3)		
5	Birch leaves	06.2018	Ocean Optics spectrometer USB-4000 345–1044 nm
6	Oak leaves		
7	Maple leaves		

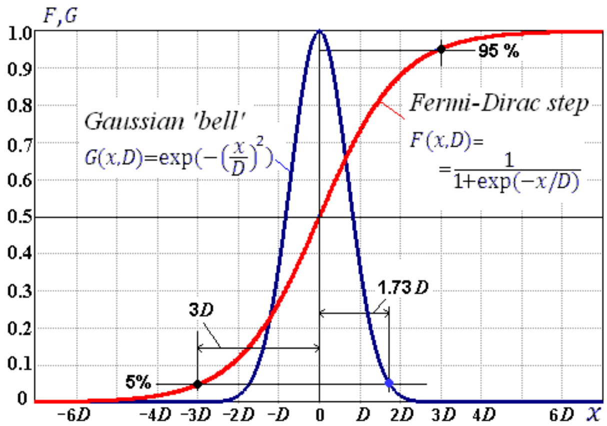

Fig. 6. Two main building blocks of the empirical compact model: Fermi-Dirac step and Gaussian bell functions.

5. CONSTRUCTION OF THE MATHEMATICAL MODEL

The typical form of GVR spectra was demonstrated above in Figs 1–5. In the considered wavelength region of 400–900 nm the two most important features to be modelled are the red edge step near 700 nm and the green apex near 550 nm. In order to maintain the quality of the mathematical model, it is reasonable to avoid all discontinuities. To accomplish this task, we decided to use for the modelling of the red step the Fermi-Dirac like distribution function (mathematically also the sigmoid function) known from semiconductor and quantum physics [26,27]:

$$F(x,D) = \frac{1}{1+\exp(-x/D)}, \tag{1}$$

where the first parameter x serves for step wavelength specification and D is the step width parameter. A good practical estimation for the step width is the change of argument from $-3D$ to $+3D$ (see Fig. 6).

Next, to model the green apex peak, the appropriate estimation may be achieved by applying the Gaussian 'bell' function:

$$G(x,D) = \exp(-(x/D)^2), \tag{2}$$

where the first parameter x serves again for peak wavelength specification and D is the step width parameter (see Fig. 6). To model the asymmetric peak, the wavelength-dependent parameter D may be used.

The actual formulas of the model are the following:

- The ground level component including the possible smooth slope between the ultraviolet and infrared ends via introducing relative amplitude parameter K_{01}

$$g(\lambda) = K_{01} + (1-K_{01})F(\lambda - 550\text{nm}, 40\text{nm}), \tag{3}$$

where the parameter 40 nm assures a nearly linear slope of the ground level between the wavelengths of 430 nm and 670 nm.

- The green apex component at wavelength λ_0

$$a(\lambda) = K_0 G\big(\lambda - \lambda_0, D_a(\lambda)\big), \tag{4}$$

where the wavelength-dependent width parameter includes a constant term D_0 and two additions near 600 nm and 640 nm to model the experimentally observed minor bumps near those wavelengths:

$$D_a(\lambda) = D_0 + D_0 K_{600} G(\lambda - 600\text{nm}, D_{600}) + D_0 K_{640} G(\lambda - 640\text{nm}, D_{640}). \tag{5}$$

- The red edge step component to describe relative rise K_{12} of the spectrum between wavelengths λ_1 and λ_2

$$s(\lambda) = K_{12} F(\lambda - \lambda_{12}, D_{12}) \tag{6}$$

with the central wavelength $\lambda_{12} = (\lambda_1 - \lambda_2)/2$ and step width $D_{12} = (\lambda_2 - \lambda_1)/6$.

- The linear slope addition to the infrared plateau

$$p(\lambda) = K_{23}\frac{\lambda-\lambda_2}{\lambda_3-\lambda_2} F(\lambda - \lambda_2, 1\text{nm}), \tag{7}$$

where the last auxiliary step function term F with a small width parameter of 1 nm is introduced to suppress the negative values below the left border wavelength of the plateau at λ_2.

- The final summing up formula for the reflectance spectrum

$$R(\lambda) = g(\lambda) + a(\lambda) + s(\lambda) + p(\lambda). \tag{8}$$

The composition of the GVR spectrum curve from four addable components of Eq. (8) is explained in Fig. 7.

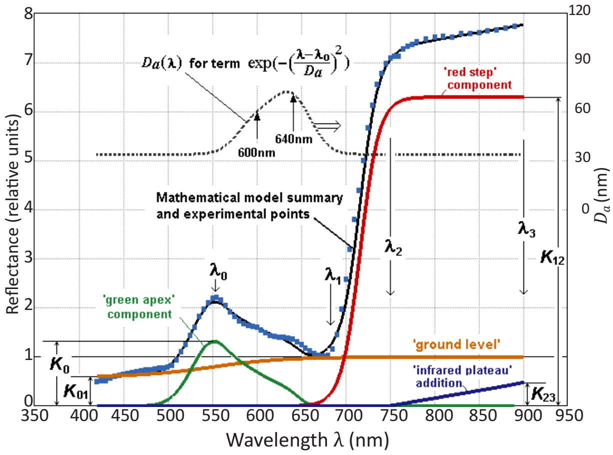

Fig. 7. Composition of the green vegetation reflectance spectrum model from four addable components: slanted ground level, green apex, red edge step and infrared plateau. The definition of four adjustable K-parameters and mostly fixed four λ-parameters is shown. In order to model the two minor bumps of the green apex at 600 nm and 640 nm, the width parameter D_a of the Gaussian function is increased near the respective wavelengths.

It is expected that in the case of reasonably well adjusted model (1)–(8), the wavelength-related parameters λ_0, λ_1, λ_2, λ_3, D_0, K_{600}, D_{600}, K_{640}, and D_{640} may have common values for all green vegetation objects and only four amplitude-related parameters K_{01}, K_0, K_{12}, and K_{23} may remain different for different green vegetation objects. In the case of a maximally compact model with only two adjustable parameters K_0 and K_{12}, the approximate estimation values should be assigned to the other two amplitude parameters K_{01} and K_{23}, e.g. $K_{01} = 1$ and $K_{23} = 0$.

As a remark it should be mentioned that the relative step height parameter K_{12} is related to the popular normalized difference vegetation index [1,2] by the following transition formula:

$$NDVI = \frac{K_{12}}{K_{12} + 2}.$$

6. MODEL TESTING AND TUNING

In order to test the proposed mathematical model and, in particular, to verify the hypothesis of the existence of common wavelength-related parameters, a parameter fitting procedure on the basis of the available seven data sets in Fig. 5 was performed. To minimize the model and measurement difference, the root mean square (RMS) measure was applied together with a minor additional suppression of the difference in the red edge step region where small horizontal shifts amplified the model and experiment differences too much. The overall result of fitting is illustrated by Fig. 8.

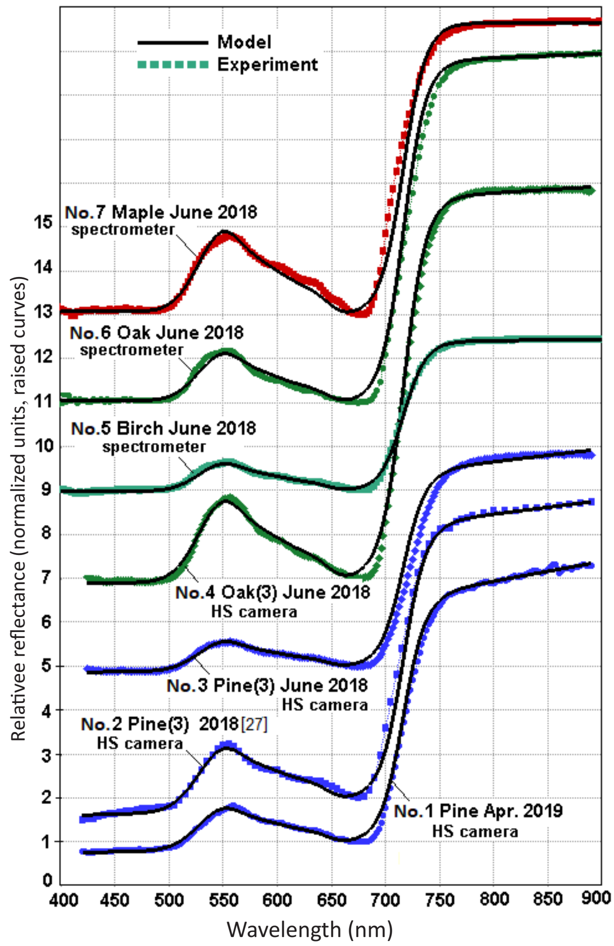

Fig. 8. Green vegetation reflectance compact model fitting results for seven experimental data sets from Table 2. Curves are presented in normalized units and raised up by different values for better readability. The four amplitude parameters are different for each data set and shown in Table 3. The nine wavelength-related parameters use the common values shown in Table 4.

The fitted K-parameters characterizing the spectra amplitudes for seven data sets are shown in Table 3. Table 4 summarizes the obtained common wavelength-related parameter values for all data sets.

The main problem revealed during the tuning was that the experimental red step was actually shifted a few nanometres between data sets (e.g. the highest difference ±6 nm between data sets Nos 7 and 3). Thus, in the red step region in some wavelength points the difference between the model and the experiment could reach a value of 0.8 in relative units although the overall shape of curves remained very satisfactory. In spite of this small horizontal shift of curves and a somewhat lower abruptness of the model near the red step foot around 685 nm, in general a rather good fitting of all seven data sets was obtained as demonstrated by Fig. 8.

Table 3. Fitted amplitude parameter values of the compact model for each of the seven experimental data sets

Data set	Parameters				RMS
	K_{01}	K_0	K_{12}	K_{23}	accuracy
No. 1 Pine 04.2019	0.75	0.88	5.7	0.68	0.082
No. 2 Pine 04.2018	0.58	1.34	6.3	0.47	0.161
No. 3 Pine 06.2018	0.86	0.63	4.5	0.46	0.167
No. 4 Oak 06.2018	0.88	1.81	8.7	0.22	0.114
No. 5 Birch 06.2018	0.98	0.63	3.4	0.04	0.040
No. 6 Oak 06.2018	1.05	1.09	7.8	0.15	0.150
No. 7 Maple 06.2018	1.08	1.87	6.6	0.08	0.205

Table 4. Common wavelength-related parameter values of the compact model obtained by the fitting of experimental data of seven data sets

Parameter	Explanation	Value
λ_0	Green apex wavelength	553 nm
λ_1	Red step start wavelength	685 nm
λ_2	Red step end wavelength	749 nm
λ_3	Wavelength region end	900 nm
$(\lambda_1 + \lambda_2)/2$	Derived secondary parameter λ_{12} – red step midpoint	717 nm
D_0	Green apex width	35 nm
D_{600}	Minor 600 nm bump width	30 nm
D_{640}	Minor 640 nm bump width	30 nm
K_{600}	Minor 600 nm bump strength	0.45
K_{640}	Minor 640 nm bump strength	1.0

7. AN EXAMPLE OF MILITARY APPLICATION

The constructed model (1)–(8) with parameter values from Table 3 and Table 4 may be used for different civil and military applications where estimation of the natural forest background spectrum is needed. Figure 9 presents a comparison of the measured spectrum of an actual pine forest, calculation by the compact model, and the measurement of a standardized colour RAL 6031 for military vehicles.

Results in Fig. 9 show that the masking colour RAL 6031 imitates quite well the red edge step and the green apex of the natural forest background reflectance spectrum. Still, some noteworthy shifts of 17–19 nm size exist, which may be identified by sophisticated equipment. At the same time the developed here model (wavelength-related parameters adjusted not to this particular forest example but to the average of seven data sets shown in Table 4) describes with nearly excellent accuracy the reflection spectrum of pine forest.

Therefore, the developed here model has prerequisites to become an easily usable working tool for situations where the real measurement data are incomplete or their usage is uncomfortable.

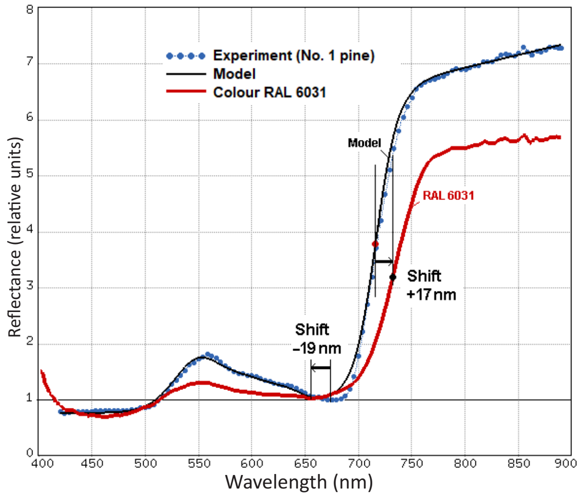

Fig. 9. Comparison of the reflectance spectrum of a standard masking colour RAL 6031 with an experimental pine forest spectrum and the compact GVR model with four amplitude parameters fitted for the actual pine forest. While the model simulates with a nearly excellent accuracy the real forest, the critical wavelengths of the masking colour are somewhat shifted from the respective values of the real forest.

8. CONCLUSIONS

In this study we proposed a compact empirical mathematical model COMSPECT for the green vegetation reflectance spectrum range of 400–900 nm. Under compactness we mean that the model contains a limited number of algebraic formulas and it needs only a few easily measurable setup parameters to specify the full spectrum. The model is constructed as a sum of four observable components: ground level, green apex, red edge step, and infrared plateau. Via the tuning procedure against the seven available data sets measured by two spectroscopic devices, we demonstrated that the common typical wavelength-related parameters for the green apex and red step may be found.

The developed model of the typical green vegetation reflectance spectrum may be used in different remote sensing and artificial objects hiding or detecting tasks where the spectroscopic signature of the natural background plays an important role and where the actual measurement data are unavailable or incomplete or there is no expert time for thorough research with sophisticated bio-optical models of PROSPECT and PROSAIL type. As an application example, testing against one standard masking colour showed a good accuracy and usefulness of this easy to use model.

In conclusion, it may be said that the COMSPECT model is capable of describing the green vegetation reflectance spectrum in the wavelength range of 400–900 nm with acceptable accuracy with only four parameters defined. It is possible to use the model for rough estimations also in a maximally compact form specifying only two most important parameters of the GVR spectrum: the relative heights of the green apex and the red edge step.

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COMSPECT: rohelise taimestiku peegeldusspektri kompaktmudel lainepikkuste vahemikule 400–900 nm

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On välja pakutud rohelise taimestiku peegeldusspektri kompaktne empiiriline matemaatiline mudel nähtava valguse ja lähiinfrapuna lainepikkustele 400 kuni 900 nanomeetrit. Mudel võimaldab lihtsustada küberfüüsikaliste süsteemide väljatöötlust mitmesugustele tsiviil- ja sõjanduslikele rakendustele, kus on vaja eristada või varjata loodusfooni taustal asuvaid tehisobjekte. Kasutades hüperspektraalselt mõõdetud spektreid ja simulatsioone täpsete biooptiliste mudelitega PROSPECT ja PROSAIL taimelehtede ning puuvõrade kirjeldamiseks, on välja pakutud minimaalse arvu häälestusparameetritega kompaktne mudel COMSPECT. On näidatud, et kui klorofüllist põhjustatud 670 nm miinimum võrdsustada ühikuga, on võimalik defineerida vaid nelja põhilise häälestusparameetriga empiiriline mudel suhtelistes ühikutes. Mudel kasutab Fermi-Diraci tüüpi astet ja Gaussi jaotust kirjeldavaid algebralisi funktsioone nelja põhilise empiiriliselt jälgitava spektrikomponendi modelleerimiseks: tasane või kaldega alusnivoo, roheline tipp, punane aste ja infrapunapiirkonna platoo. Mudeli testimine ja parameetrite häälestamine on teostatud seitsme komplekti katseliste spektrite alusel, mis on mõõdetud hüperspektraalkaamera ning kompaktse spektrograafi abil. Väljatöötatud mudeli kasuliku rakenduse näitena on esitatud militaarse maskeerimisvärvi RAL-6031 spektraalsignatuuri analüüs. Lisaks on töös näidatud, et mudel on kasutatav ligikaudsete hinnangute jaoks ka vaid kahe häälestusparameetriga, milleks on rohelise 550 nm tipu ja punase 700 nm astme suhtelised kõrgused.