

THE USE OF RADIATION TRANSFER MODELLING FOR THE EXTRACTION OF BIO-GEOPHYSICAL VARIABLES

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ABSTRACT

Natural surfaces, such as vegetation and soil, do not - as a rule - reflect incident solar radiation equally in all directions. This reflectance anisotropy is formally described by a **Bidirectional Reflectance Distribution Function (BRDF)**. Radiation transfer models have their foundation in the theory of radiation transfer for turbid as well as discrete media, and in the physical principles of geometric-optics. It is possible to invert 'physically-based' radiation transfer models against a limited set of measurements of surface-leaving radiation. At different wavelengths and with acquisitions obtained with different observation geometries (solar illumination and sensor viewing angles), parameter values for a parametric BRDF model can be determined. A sufficient number of multi-angular observations must be used, to obtain a statistically meaningful extraction of bio- geophysical variables.

Classical radiation transfer (RTF) theory is a physically based approach, to study radiation transfer in vegetation canopies and to retrieve vegetation bio- geophysical variables. Though the classical approach is applicable for homogeneous canopies (grasses, certain crops), a major limitation is that it is definitely not applicable for natural vegetation which exhibits spatial heterogeneity. Special attention is given therefore to the inclusion - in the RTF modelling environment - of different generic biome types and the effect of the spatial discontinuity of vegetation on the radiation field in the canopy. Account is taken of the evolution of radiation transfer modelling, from the description of simple homogeneous media (turbid medium approach), to discrete and therefore complex media which require the discrete ordinates method to solve the RTE (**Radiation Transfer Equation**).

The first results with regard to the convergence of the RPV model parameterization technique, are presented. This convergence is a strong requirement for a successful extraction of bio- geophysical variables using VGT-P imagery. In short, this paper gives a status description of the PDRS (**Prospect – Disord – Rahman – 6S**) coupled radiation transfer environment, for the extraction of bio-geophysical variables.

KEYWORDS: Radiation transfer modelling, multi-angular observations, bio- geophysical variable extraction, model inversion, VGT-P.

1. INTRODUCTION

Natural surfaces, such as vegetation and soil, do not generally reflect incident solar radiation equally in all directions. This reflectance anisotropy – formally described by a **Bidirectional Reflectance Distribution Function (BRDF)** – is controlled by the physical structure of a **Soil – Vegetation – Atmosphere (SVA)** continuum e.g., the density and 3-D arrangement of plant leaves and stems, the surface roughness of soils and the optical as well as scattering properties of atmospheric components (Myneni and Ross, 1991). A large set of models has been developed in the past to describe these relationships (Gobron et al., 2000). Many have their origin in the theory of radiation transfer in turbid media and in the physical principles of geometrical optics (Myneni, 1995).

To retrieve the physical properties of a SVA continuum, 'physically-based' **Radiation Transfer** models (RTF's) are inverted using a limited set of directional as well as spectral measurements of SVA leaving radiation. For different sensor wavelength bands – each sampled with a different observation geometry (see figures 1 and 2) $\Omega = (\theta_s, \theta_w, \phi_r)$ - the parameter values for semi-empirical BRDF models can be determined and used to retrieve key bio- geophysical properties of a SVA

continuum. Since the interaction of light with a SVA continuum of heterogeneous and discrete nature, results in the generation of an anisotropic reflectance field, observed angular reflectance distributions can be used in addition to surface spectral signatures, to characterize the SVA, provided that:

- models are available describing how anisotropy results from elementary light scattering processes (Stamnes et al., 1988) and;
- inversion procedures are available to exploit this opportunity (Leroy et al., 1997 and Gobron et al., 2000).

The RTF environment applied to generate a **Look-Up-Table (LUT)** for inversion purposes is called the PDRS environment. The PDRS canopy RTF was developed at the Department of Geography of Boston University (Myneni et al., 2002). Further development of the model at the level of leaf reflectance modelling was based on the leaf RTF PROSPECT (Jacquemoud and Baret, 1999). A triplet (or quartet) parameterization method is based on the **Rahman–Pinty–Verstraete (RPV)** function (Rahman et al., 1993). The inversion procedure, the incorporation of spectral band response functions (SRF's), the development of a *f*APAR

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and broadband albedo estimation procedure, a SVA scenario generator, LUT generation and output controls of the code, have been developed by VITO as well as the full coupling and integration of all PDRS code subroutines and functions.

The inversion method is based on merit function minimization, using three or four RPV parameters (triplets, quartets). These are estimated with a multi-temporal series of VGT-P data. The image pixel quartet is then compared with all quartets collected in a LUT, simulated with PDRS according to specific SVA scenarios. When the merit function is minimal for all sensor (VEGETATION) spectral bands, the bio- geophysical variables for a target object in the SVA continuum are extracted from the LUT record which corresponds with the before mentioned minimum value of the merit function. A sufficient number of multi-temporal observations must be used to extract bio- geophysical variables with an uncertainty which is statistically sufficiently low. Evidently, when a platform-sensor combination has multiple viewing capacity, model inversion is reached with shorter time intervals. Finally, when the retrieval index for a region of interest (ROI) is high enough, retrieved bio- geophysical variables can be mapped for the specific ROI.

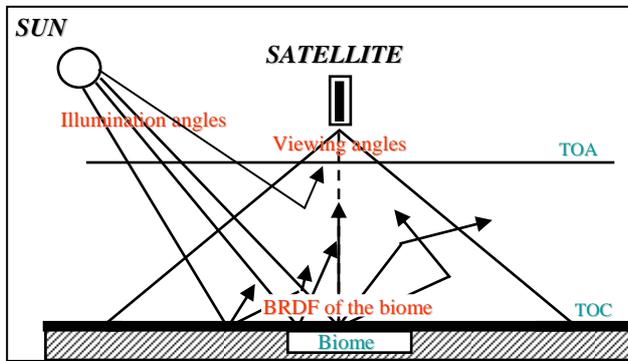


Figure 1. Conventions for satellite observation geometry $\Omega = (\theta_s, \theta_v, \phi_r)$ for a passive optical remote sensing platform at nadir. Note that TOA is Top-Of-the-Atmosphere and TOC is Top-Of-the-Canopy.

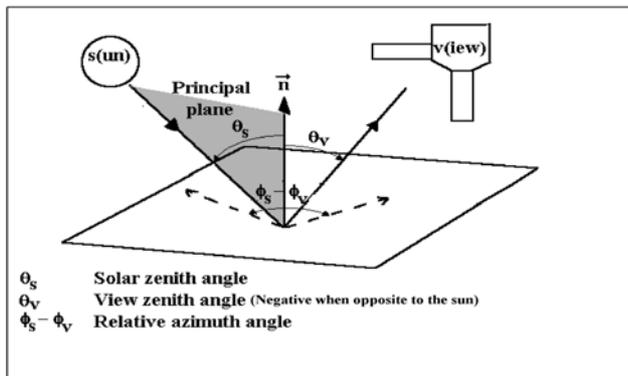


Figure 2. The different satellite observation angles of sun illumination and satellite viewing for an optical remote sensing platform. Note the principal plane and the relative azimuth angle $\phi_r = \phi_s - \phi_v$.

2. DESCRIPTION OF THE PDRS MODELLING ENVIRONMENT

PDRS is a Soil – Leaf – Canopy - Atmosphere (SLCA) coupled RTF modelling environment. It consists of a soil BRDF

model which - as the lower boundary of the SVA - can be specified as an isotropic or anisotropic reflector. Further development is on its way to specify soil spectral signatures in function of organic or mineral content and most importantly, soil moisture content (SMC). The leaf model used in the PDRS environment is PROSPECT as developed by Jacquemoud and Baret (1999). The PROSPECT model output, e.g., spectral leaf reflectance is simulated by this model in function of – most importantly- leaf chlorophyll and water content. The output of PROSPECT is an input for the canopy RTF model DISORD, as developed by Myneni et al. (2002).

PDRS is applied in forward mode to generate a TOC LUT as outlined in figure 3.

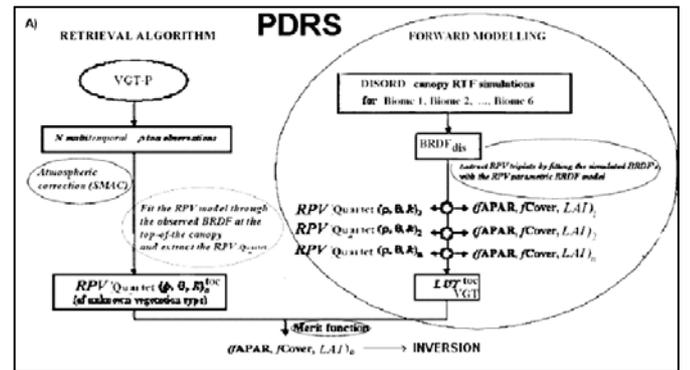


Figure 3. The PDRS RTF modelling environment in TOC conditions and with its forward modelling segment (right circle) as well as its retrieval algorithm for bio- geophysical variables (left part of the scheme).

The TOC LUT is used for model inversion purposes and includes three (or four) parameters of the RPV function (Rahman et al., 1993). The RPV function is defined as follows:

When... $\Omega = (\theta_s, \theta_v, \phi_r)$

$$BRF_{\lambda}(\Omega) = RPV_{\lambda}(\Omega, k_{\lambda}, \Theta_{\lambda}^{hg}, \rho^*_{\lambda}) = f_1(\theta_s, \theta_v, k_{\lambda}) f_2(\Omega, \Theta_{\lambda}^{hg}) f_3(\Omega, \rho^*_{\lambda}) \dots (1)$$

where,

$$f_1(\theta_s, \theta_v, k_{\lambda}) = \frac{(\cos \theta_s \cos \theta_v)^{k-1}}{(\cos \theta_s + \cos \theta_v)^{1-k}} \dots (2)$$

$$f_2(\Omega, \Theta_{\lambda}^{hg}) = \frac{1 - \Theta_{\lambda}^{hg^2}}{[1 + \Theta_{\lambda}^{hg^2} - 2\Theta_{\lambda}^{hg} \cos(\pi - g)]^{3/2}} \dots (3)$$

$$f_3(\Omega, \rho^*_{\lambda}) = \rho^*_{\lambda} \left[1 + \frac{1 - \rho^*_{\lambda}}{1 + G} \right] \dots (4)$$

with

$$\cos(g) = \cos \theta_s \cos \theta_v + \sin \theta_s \sin \theta_v \cos \phi_r$$

hence, $g = \arccos(g)$

in equation (3)

$$G = \sqrt{\tan^2 \theta_s + \tan^2 \theta_v - 2 \tan \theta_s \tan \theta_v \cos \phi_r}$$

in equation (4)

The triplet is: $\rho^*_{\lambda}, \Theta_{\lambda}^{hg}, k_{\lambda}$

$BRF_{\lambda}(\Omega)$ characterises the anisotropy of the SVA medium in terms of three (or four) unknown parameters (triplets or quartets) which are characteristic for the type of SVA and for a given spectral band B_{λ} . The function f_1 is a combined form of the Minnaert and Lommel-Seeliger functions. The function f_2 is the single-term Henry-

Greenstein function used to describe the phase function of aerosol scattering. The function f_3 is used to describe the hotspot feature of the BRDF. The RPV model has for example been used in the production of MISR land surface products (Diner et al., 1998).

The atmospheric RTF (SMAC: Simplified Model for Atmospheric Correction) is applied to atmospherically correct VGT-P products, before they are used for bio- geophysical variable extraction when the atmosphere is ignored in LUT generation (TOC LUT). Inversion is based on the parameterization of the RPV function for a specific pixel, for all sensor spectral bands as well as for all useful observations (Ω). This enables the evaluation of a merit function (see figure 3) which - when minimized - is the retrieval engine for a record of the LUT, corresponding with the merit functions minimum. Under those conditions, inversion is obtained and the bio-geophysical variables from the LUT record can then be retrieved for the pixel being processed. Clearly each LUT record is characterized by a triplet (or quartet), e.g. the three (or four) parameters of the RPV function. Each LUT record corresponds with a specific SVA scenario case.

3. FORWARD MODELLING WITH PDRS

In this chapter examples are given of the steps needed in forward modelling mode, to generate a TOC LUT. First and not least important is the specification of the observation (Ω) conditions. Clearly, when dealing with a satellite sensor/platform combination, the observation geometries have to be generated with an orbital model specific for the satellite mission under consideration. A few examples are given in figure 4, for the VEGETATION1 mission.

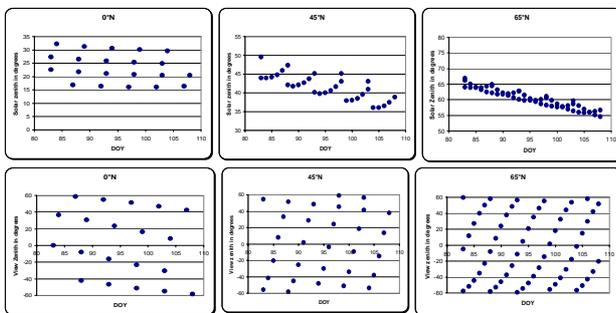


Figure 4. Solar (panes above) and view zenith (panes below) angles for latitudes of 0, 45 and 65 °N (panes from left to right) generated with an orbital model for the VEGETATION1 mission as used in PDRS and for a 26 day revisit cycle.

Subsequently, the spectral response characteristics of the sensor bands used have to be specified. In case of PDRS this not only means specification of the Spectral Response Functions (SRF's) of the sensor spectral bands, but also for example the spectral characteristics of a PAR quantum sensor (see figure 5).

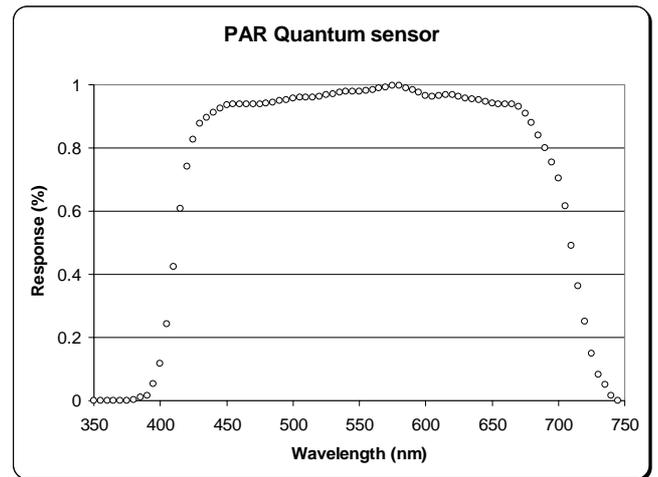


Figure 5. The spectral response function of a PAR quantum sensor.

Canopy absorbed PAR as simulated using a PAR quantum sensor SRF, is used to calculate $fAPAR$, an important bio- geophysical variable needed to evaluate carbon relations or plant productivity.

When observation (Ω) conditions and SRF's are specified, the next input in PDRS is leaf reflectance. To this end the leaf RTF model PROSPECT (Jacquemoud S. and Baret F. , 1999) is used. Table 1 summarizes - for each biome in PDRS - the leaf chlorophyll and water content input ranges (making part of a LUT simulation scenario).

Table 1. Biome (DISORD) dependent PROSPECT inputs for leaf chlorophyll and water content.

Biome	Biome nr.	C_{ab} ($\mu\text{g}/\text{cm}^2$)	C_w (cm)	Leaf geometry
Grasses and cereal crops	1	1 - 50	0.0002 - 0.015	Erectophyle
Shrubs	2	43 - 52	0.013 - 0.015	Uniform
Broadleaf crops	3	20 - 40	0.005 - 0.025	Uniform
Savanna	4	17 - 35	0.005 - 0.010	Erectophyle
Broadleaf forests	5	26 - 52	0.007 - 0.015	Planophyle
Coniferous forests	6	52 - 70	0.015 - 0.021	Planophyle

Figure 6 illustrates the output of the PROSPECT leaf RTF model, of which only the spectral reflectance signature (blue curve) is used as input for the DISORD canopy RTF.

Once the before mentioned inputs have been specified, a last step consists of specifying the inputs of the DISORD canopy RTF. These inputs are summarized in tables 2 and 3.

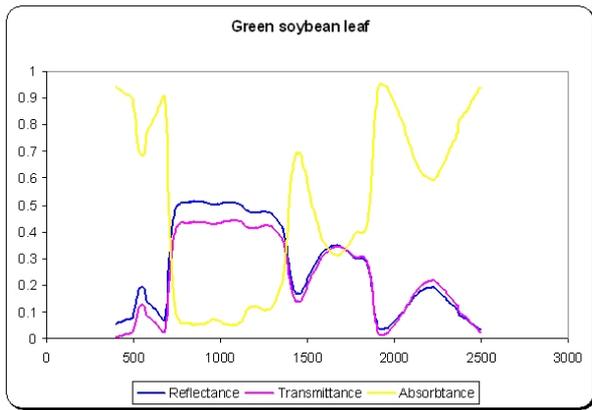


Figure 6. Simulation of soybean leaf reflectance, transmittance and absorbance. The simulation has been performed with biome 3 leaf level inputs as cited in table 1.

Table 2. Biome specific attributes for the canopy RTF DISORD.

Attributes	1	2	3	4	5	6
Grasses and Cereal crops	Grasses and Cereal crops	Shrubs	Broadleaf crops	Savannah	Broadleaf forests	Needleleaf forests
Horizontal heterogeneity	No	Yes	Variable	Yes	Yes	Yes
Ground cover	100 %	20-60%	10-100%	20-40%	>70%	>70%
Vertical Heterogeneity (leaf optics and LAD)	No	No	No	Yes	Yes	Yes
Stems/Trunks	No	No	Green stems	Yes	Yes	Yes
Understorey	No	No	No	Grasses	Yes	Yes
Foliage dispersion	Minimal clumping	Random	Regular	Minimal clumping	Clumping	Severe clumping
Crown shadowing	No	Not mutual	No	No	Yes mutual	Yes mutual
Brightness of canopy ground	Medium	Bright	Dark	Medium	Dark	Dark

Table 3. Parameter input ranges for the canopy RTF DISORD

Parameter	Grasses/ Cereals Crops	Shrublands	Broadleaf Crops	Savanna	Leaf Forests	Needle Forests
Plant LAI	0 - 7	0 - 7	0 - 7	0 - 7	0 - 7	0 - 7
Fractional Ground Cover	1.0	0.2 - 0.6	0.1 - 1.0	0.2 - 0.4	> 0.8	> 0.7
Understorey LAI	n/a	n/a	n/a	0 - 5	0 - 2	0 - 2
Leaf Normal Orientation	erectophile	uniform	uniform	uniform/erectophile	uniform/platanophile	uniform/platanophile
Stems, Trunks & Branches	n/a	5%	10%	10%	15 - 30%	15 - 30%
Leaf Size (m)	0.05	0.05	0.10	n/a	n/a	n/a
Crown Size (m)	n/a	n/a	n/a	4x2 8x4	6x4 12x8	4x2 8x4
Soil Properties c = clay, s = sand	60c+40s medium	80c+20c bright	80c+20s dark	60c+40s medium	60c+40s medium	60c+40s medium

Figure 7, illustrates the biome specific BRDF's obtained with forward simulation runs of PDRS for the VEGETATION1 RED spectral band.

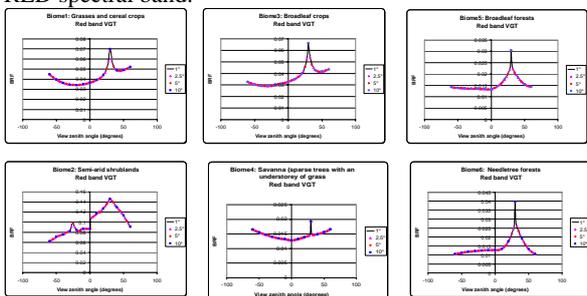


Figure 7. Biome specific BRDF's obtained with forward simulation runs of PDRS for the VEGETATION1 red spectral band. Panes above from left to right: biomes 1, 3, 5. Panes below from left to right: biomes 2, 4, 6.

Clearly each DISORD biome elicits a specific shape of the BRDF, characterized by specific hot spot shapes in the backscatter direction and convex, concave or more or less flat bidirectional reflectances over the valid view angle range. The

discretization of the view angle does not have an influence on the shape of the BRDF's. The next phase in PDRS application is the parameterisation of the RPV function and the generation of a TOC LUT.

4. CONVERGENCE OF RPV MODEL PARAMETERIZATION AND PDRS MODEL INVERSION USING A TOC LUT

To be able to achieve RTF model inversion and hence, bio- geophysical variable extraction for an image element, a frequently applied method is the use of a LUT. With PDRS the LUT is generated based on scenario runs in forward simulation mode (see figure 3). In the PDRS environment we make use of the RPV function and especially its parameters (e.g., a triplet or quartet) to achieve model inversion. After parameterization for a specific scenario case, the corresponding RPV parameters are stored in a LUT record. After LUT generation they will serve to evaluate the inversion merit function (see figure 3). This merit function compares (by calculating the RRMSE or (Relative Root Mean Square Error) the LUT triplet entries with an observed RPV triplet for a specific spectral band and for a VGT-P pixel being processed. The observed RPV parameters are obtained by collecting multi-temporal series of VGT-P observations. This enables the parameterization of the observed RPV function. The observed RPV triplet is then compared (RRMSE) with the same parameters as stored in a LUT record. When the (inversion) merit function for a triplet (or quartet) pair is minimal for all records in the LUT, inversion is obtained. As can be seen in figure 3, bio-geophysical variables can be extracted representative for the time period needed to obtain optimal parameterization of the (observed) RPV function using atmospherically corrected (SMAC) VGT-P data.

Obviously, each record entry in the LUT requires a parameterization of the RPV function based on the simulated DISORD BRDF's. The match of a forward simulated BRDF with an observed BRDF is purely based on the triplet (or quartet) obtained by parameterization of the RPV function. In figure 8, the match between a TOC BRDF simulated with PDRS and an optimally parameterized RPV function, is illustrated.

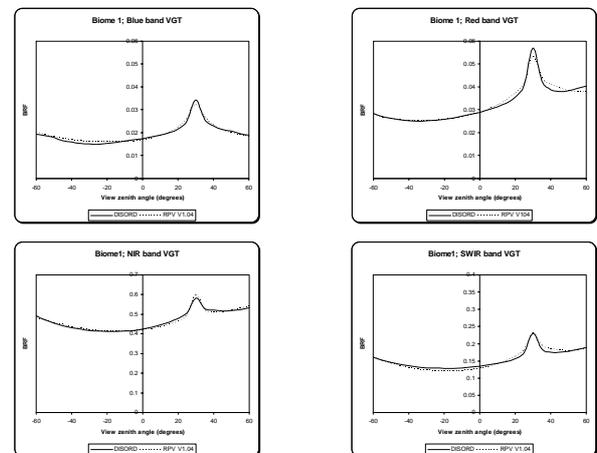


Figure 8. Forward simulated BRDF, and the match after parameterization of the RPV function with the DISORD BRDF for biome 1 and for all spectral bands of VEGETATION1.

Note the small differences between the two BRDF's for all spectral bands of VEGETATION1. Also note the reflectance differences in magnitude as well as in shape of the BRDF in function of the spectral band number. Note that the hot spot is at its largest for the RED band. This is expected, since for that wavelength range, absorbance is maximal and hence shadowing as well. For the NIR band the hot spot is at its smallest, because of the high transmission in this wavelength region.

Figure 9. illustrates the convergence process for the RED and NIR bands of VEGETATION1. For both these bands, the RRMSE drops below 0.1 % after 1.00E+04 iterations. The ρ_λ and k_λ RPV parameter values stabilize after 1.00E+04 iterations as well. The convergence to a stable value for the Θ_λ^{hg} RPV parameter takes more iterations for the RED band than for the NIR band of VEGETATION1. Note that the RPV parameter values are strongly dependent on spectral band number. This suggests that the combination of multi-spectral and multi-angular observations in a merit function for biogeophysical variable extraction, will lead to a higher retrieval index (efficiency) for bio- geophysical variable extraction, than the separate use of both.

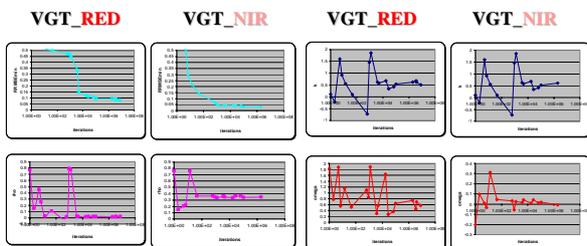


Figure 9. Light blue curves, convergence of the RRMSE for the RED and NIR band of VEGETATION1 in function of the number of iterations of the parameterization algorithm. Dark blue, pink and red curves, convergence of the triplet parameter values (ρ_λ , k_λ , Θ_λ^{hg}) for the RED and NIR bands towards a stable value in function of the number of iterations.

Figure 10, shows the regression curves - after convergence and for all VEGETATION1 spectral bands – between the RPV BRDF and the simulated DISORD BRDF for biome 1. The regression coefficients are practically identical for all bands (0.97 – 0.98). The slope deviates from the 1:1 line by 3 to maximally 15%. Intercepts for all spectral bands are practically zero.

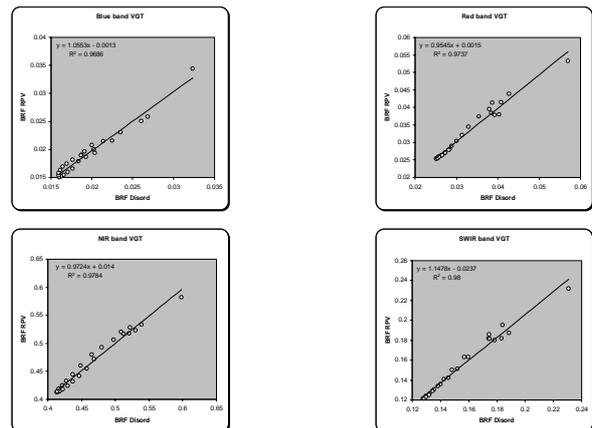


Figure 10. Regression curves - after convergence and for all VEGETATION1 spectral bands – between the RPV BRDF and the simulated DISORD BRDF for biome 1.

5. CONCLUSIONS

A new integrated modelling environment (PDRS) for bio- geophysical variable retrieval, has been developed and tested in forward mode. Though the classical approach is applicable for homogeneous canopies (grasses, crops), a major limitation is that is inaccurate for natural vegetation, exhibiting spatial heterogeneity (forests, savannah's or shrubs exhibiting mutual shadowing and gaps).

The RTF environment accommodates for forward modelling purposes, as well as for inversion purposes. The inversion technique is based on the use of a TOC LUT obtained by forward modelling and RPV parameterization. The model is fully operational in forward mode and makes use of several sub-models for the generation of observation geometries (orbital models for LANDSAT, NOAA-AVHRR and VEGETATION), the PROSPECT model for leaf RTF, the DISORD model for canopy RTF. A future development is the coupling with atmospheric radiation transfer model 6S in forward mode. This approach typically has the potential for retrieval of information on atmospheric aerosol (Leroy et al., 1997, North et al., 1999). The retrieval code of PDRS is being tested at this moment in time.

Furthermore, PDRS accommodates for RTF in heterogeneous vegetation canopies with mutual shading. PDRS solutions are dependent on biome type (6 types). PDRS inversions are based on multiple spectral band LUT's and hence makes use of the full multi-spectral capacity of a sensor or multiple sensors. PDRS inversion is optimized to obtain solutions using Look-up Tables (LUT's) and makes use of the strong discriminating capacity of a combination of multi-spectral as well as multi-angular observations.

In future work, the bio- geophysical products generated by the use of PDRS and VGT-P will be validated using the VALERI approach.

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7. ACKNOWLEDGEMENTS

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