Report on the validation of MERIS TOC_VEG land products

F. Baret, C. Bacour, M. Weiss, B. Berthelot,

March 2006

Contract ESA AO/1-4233/02/I-LG

Table of contents

1. Introduction

The objective of this study is to provide some validation elements of the LAI, fAPAR and fCover products derived from the TOA_VEG algorithm (Baret, Pavageau et al., 2006). The algorithm accepts as inputs the top of atmosphere reflectance values as derived from MERIS L1b images.

The validation is the process of assessing by independent means the accuracy of data products derived from the system outputs (Justice, Starr et al., 1998). This will provide the confidence intervals that ire mandatory for the users in a number of applications, including those based on a data assimilation approach. However, the validation is a very difficult task particularly regarding the extent of the products (the globe), the spatial resolution (from 300m to 1km), as well as the dynamics of the vegetation. Therefore, the results that will be presented here after could only be considered as a preliminary step before a more rigorous validation exercise. However, the results presented here after, although limited because of the restricted resources available, are approaching those acquired through the validation activity around the MODIS products which beneficiate from a far larger amount of support…

The validation is generally achieved through two main approaches:

- ***Direct validation*** which consists in the comparison of the products to ground measured values of the corresponding biophysical variables. Direct comparison with ground measurements have been achieved over a limited number of sites and dates. The few sites and dates that have been sampled during these last years provide high spatial resolution maps of the biophysical variables considered as derived from local ground measurements that have been up-scaled thanks to SPOT or TM high spatial resolution images. However, in addition to the question of the proper uncertainty associated to this ground validation exercise, the necessary small number of sites sampled questions the representativity of this sampling with regards to the global extent targeted. The same applies to the temporal sampling, particularly regarding the large seasonal variation observed for some vegetation types. In this study, we focused on three different sets of ground measurements that took place over a relatively wide range of situations.
- ***Indirect validation*** that should rather be termed ‘evaluation’ because it provides only insight into the relative values (from date to date, from place to place, from product to product) of the products. Inter-comparison would be very useful to complement the direct validation exercise by providing a far better sampling, both in space and time because it does not require any ground measurements. In addition, inspection of the smoothness of the time course of the biophysical products at a given site would also yield key information on the sensor and the performances of the algorithms with regards to cloud screening, atmospheric correction, BRDF effects, and soil background possible variations. In this study, we mainly focused on the comparison of our MERIS products to the corresponding ones derived from MODIS, CYCLOPES, ECOCLIMAP, and MERIS-MGVI products. Concurrently, when possible, the spatial and temporal consistency of the products will be also discussed.

2. MERIS data

Twenty four sites have been selected from the BELMANIP network (Baret et al. 2006a) for the evaluation of the NN estimation performances. They correspond to different vegetation types: 17 sites belong to the VALERI project; 7 additional sites from the AERONET network (Holben et al., 1998) are also used. Each site is affixed the biome class of the dominant vegetation type, according to the typology used for the *LAI/fAPAR* MODIS products (Knyazikhin et al., 1998b): 1) grasses and cereal crops, 2) shrubs, 3) broadleaf crops, 4) savannas, 5) broadleaf forests, and 6) needleleaf forests.

name	**database**	**lat**	**lon**	**biome class**	**VALERI** ***LAI*; *fAPAR*; *fCover***
Concepcion	VALERI	-37.47°	-73.47°	broadleaf forest	3.10; 0.77; 0.46 *0.57; 0.12; 0.07*
Laprida	VALERI	-36.99°	-60.55°	savanna	
Turco	VALERI	-18.24°	-68.20°	shrub	0.03; 0.03; 0.03 *0.002; 0.002; 0.002*
Jabiru	AERONET	-12.65°	132.88°	savanna	
AekLoba	VALERI	2.63°	99.58°	broadleaf forest	
Counami	VALERI	5.34°	-53.24°	broadleaf forest	
Ouagadougou	AERONET	12.18°	-1.38°	savanna	
Banizoumbou	AERONET	13.53°	2.65°	grasses and cereal crop	
Gourma	VALERI	15.33°	-1.53°	grasses and cereal crop	
SierraCincua	VALERI	19.67°	-100.28°	needleleaf forest	
Haouz	VALERI	31.66°	-7.60°	shrub	1.19; 0.49; 0.25 *0.43; 0.13; 0.09*
Barrax	VALERI	39.06°	-2.10°	broadleaf crop	1.08; 0.28; 0.25 *0.59; 0.13; 0.11*
ZhangBei	VALERI	41.28°	114.68°	grasses and cereal crop	
Sud-Ouest	VALERI	43.50°	1.23°	broadleaf crop	
Puechabon	VALERI	43.72°	3.65°	savanna	
Avignon	AERONET	43.80°	4.70°	broadleaf crop	
Larzac	VALERI	43.95°	3.13°	savanna	
Fundulea	VALERI	44.41°	26.57°	grasses and cereal crop	0.91; 0.34; 0.29 *0.36; 0.09; 0.076*
Bordeaux	AERONET	44.71°	-0.77°	needleleaf forest	
Larose	VALERI	45.38°	-75.22°	needleleaf forest	3.58; 0. 91; 0.85 *0.24; 0.02; 0.03*
Moldova	AERONET	47.017°	28.75°	broadleaf crop	
Romilly	VALERI	48.33°	3.80°	grasses and cereal crop	
Fontainebleau	AERONET	48.40°	2.67°	broadleaf forest	
Hirsikangas	VALERI	62.52°	27.03°	needleleaf forest	

The available MERIS images over these sites consist in level 1b top of the atmosphere (TOA) reflectance data at the reduced spatial resolution (1200 m). A site extent of 3 x 3 pixels is chosen to minimize possible mis-registration and point-spread function effects as well as to be consistent with the extent of VALERI sites. To avoid non linearity effects, the NN inversions are performed per pixel and the average of the estimates over the image is then considered. The data were acquired during year 2003, covering the full vegetation cycle. MERIS level 1b TOA reflectances were corrected from atmospheric effects with the SMAC (Simplified Method for Atmospheric Correction) model (Rahman and Dedieu, 1994), once provided the atmosphere parameters of the considered scene. The ozone content used is included in the L1b product, while atmospheric pressure at the surface level and water vapour content derive from the MERIS L2 product. The aerosol optical thickness is estimated from the actual TOA reflectances measured in 13 spectral bands plus the geometry of observation by a dedicated neural network (Béal et al., 2006). The latter was previously trained over radiative transfer model simulations with the above-mentioned canopy and atmosphere models. MERIS images can be contaminated by clouds as, up to now, no efficient cloud screening algorithm was applied to MERIS level 1b products. To eliminate cloud events as much as possible, a simple test for cloud detection based on NDVI (Normalized Difference Vegetation Index) time series was used. The test is based on the assumption that sudden drops in NDVI profiles are mainly related to clouds and poor atmospheric conditions (Viovy et al., 1992). The corresponding observations are therefore discarded to keep the highest NDVI values with the smoothest temporal variation possible. Note that this will also eliminate possible poor atmospheric corrections.

The neural network is then run on the images identified as cloud-free although remaining clouds or poor atmospheric correction may degrade the estimation. Figure 1 shows the relationships between the estimated *LAI*, *fAPAR*, and *fCover*, with the respective theoretical hulls of allowed variation inferred from the training database. The co-distribution of the variable estimates is very similar to that obtained on the testing dataset.

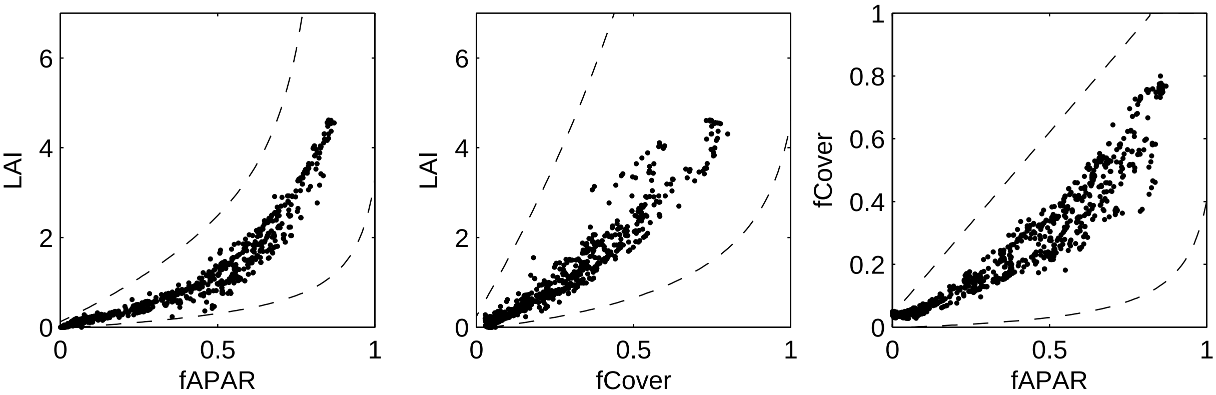

Figure 1: Scatter plots between the various biophysical variable estimates and corresponding hulls of allowed variation.

3. Validation datasets

MODIS *LAI* and *fAPAR* products (MOD15 product, collection 4) are delivered weekly for the same sites, at 1 km spatial resolution. They are derived from the inversion of a three dimensional radiative transfer model using a Look-Up Table approach, tuned for the six previously defined biomes (Knyazikhin et al., 1998b). In case of failure, a back-up estimation replaces the main algorithm. It is based on relationships between the biophysical variables and NDVI calibrated over radiative transfer simulations for each vegetation type. Note that *fAPAR*-MODIS products correspond to collection 4 reprocessed by the Boston University over the validation sites. The MERIS Global Vegetation Index (*MGVI*) (Gobron et al., 1999) is also determined for the same MERIS images. This vegetation index is optimized for the estimation of *fAPAR* (under direct illumination), while minimizing the atmospheric effects, from the top of atmosphere measurements in the MERIS channels at 442, 681 and 865 nm. *MGVI* was calibrated over simulations with a one dimensional radiative transfer model. Contrary to MODIS biophysical products, actual NN estimates and *MGVI* values do not derive from any temporal compositing. They are therefore more subject to noise due to remaining cloud contaminations and to residual variations in atmospheric conditions, as well as estimation uncertainties. In order to perform more consistent comparisons, the temporal profiles of *MGVI* and NN estimates are smoothed by applying a temporal Gaussian filter defined by a time window of 15 days and a 10-day standard deviation.

Ground truth of *LAI*, *fAPAR*, and *fCover*, are made available thanks to the VALERI project (Baret, et al., 2006b). The latter provides high spatial resolution maps of these biophysical variables for the evaluation of the estimation accuracy of the products derived from large swath sensors. A VALERI site is a 3 x 3 km² flat area, thematically homogeneous at the medium resolution scale. The biophysical maps are estimated from the concurrent use of local ground measurements and SPOT imagery. The ground measurements consist in LAI2000 measurements or hemispherical photographs providing estimates of *LAI*, *fAPAR* and *fCover*. As a consequence, the measured leaf area index corresponds to an effective *LAI* (that does not consider possible clumping effects), which is in agreement with the assumptions of the SAIL model. The estimates are then related to the corresponding SPOT radiometric data by the determination of site specific transfer functions used to extend the local ground measurements over based on the high spatial resolution SPOT image. The sites used in this study were sampled in 2003: they are namely Concepcion (Chile), Turco (Bolivia), Haouz (Morocco), Barrax (Spain), Fundulea (Romania) and Larose (Canada). The biophysical variables available for validation derive from the aggregation of the high spatial resolution image at 1km resolution. The average of the variables (and the corresponding standard deviation) over the 3 x 3 km² total site area are considered in the following. The averaging allows reducing potential residual misregistration between the VALERI sites and the MERIS or MODIS images, all data having been re-projected in UTM/WGS84.

4. Comparison to MODIS and MGVI products

The observation dates of MERIS and MODIS are not strictly concurrent, the same applying to the VALERI measurements. The following intercomparison is restricted to the data which acquisition dates do not depart from 7 days. Only small variation of the surface characteristics is therefore expected within a 7-day interval.

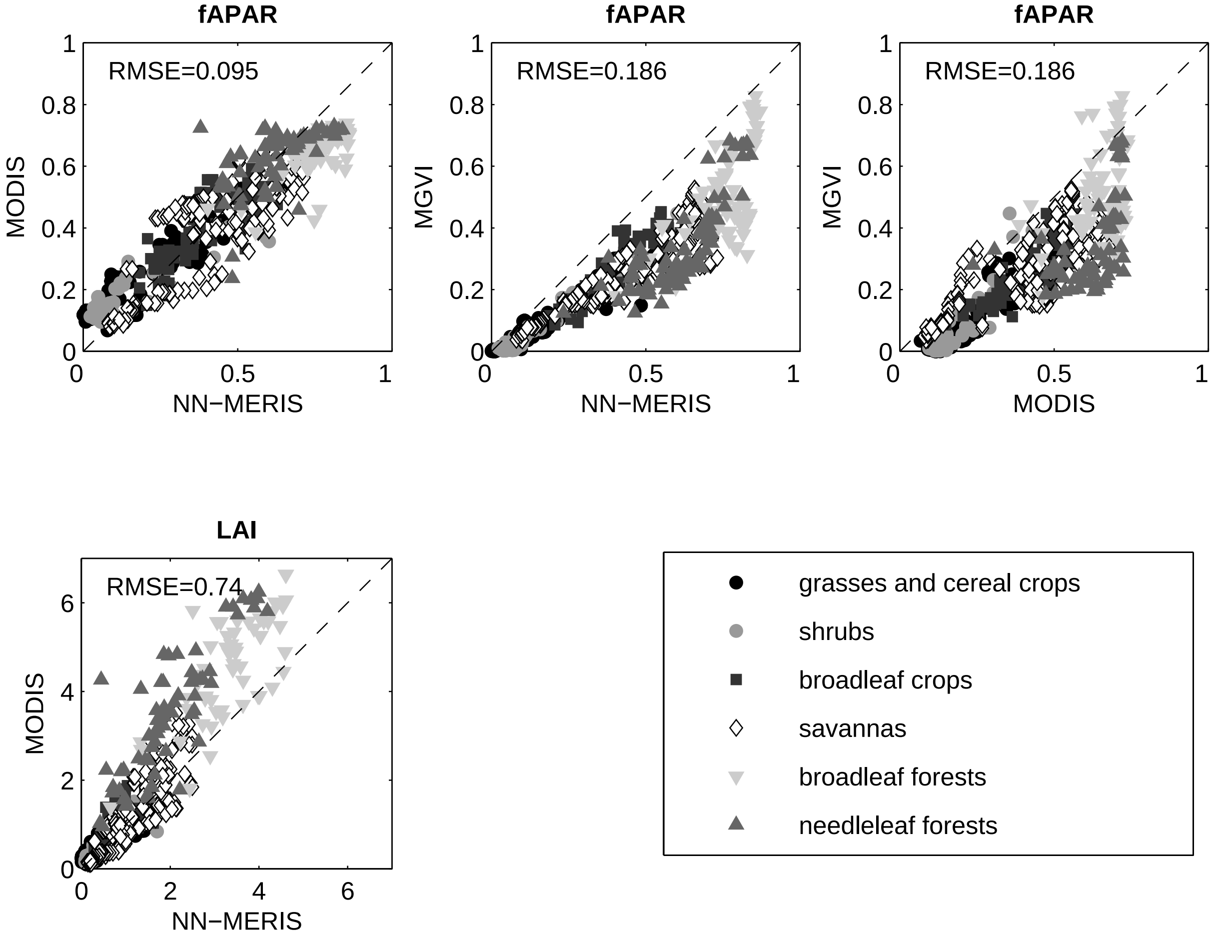

Figure 2: Scatter plots of the fAPAR (top) and LAI (bottom) estimates between the different biophysical products (MODIS, NN-MERIS, and MGVI). Each symbol corresponds to a given biome. The Root Mean Square Error (RMSE) between the estimated values taken two by two is also provided.

A good agreement between MODIS and NN-MERIS is observed both for the leaf area index (RMSE = 0.74) and *fAPAR* (RMSE below 0.1), all biomes included (Figure 2). As shown by Table 1, the differences between NN-MERIS- and MODIS- *fAPAR* estimates are similar for the various biomes.. *fAPAR*-NN-MERIS is slightly lower than *fAPAR*-MODIS for values beyond 0.6. The differences between NN-MERIS- and MODIS- *fAPAR* estimates are similar for the various biomes. Oppositely, the disagreement between *LAI*-NN-MERIS and *LAI*-MODIS is significantly greater for the densest canopies, that is broadleaf and needleaf forests. The NN estimates are lower than the MODIS products for *LAI* greater than 3 typically although a slight overestimation by the NN of actual *LAI* values between 2 and 5 (Figure 2b) was expected. The absence of clumping in our NN algorithm may partly explain this feature. On the other hand several studies have pointed out a tendency of the *LAI*-MODIS algorithm to overestimate actual leaf surface areas in the case of forests (Cohen et al. 2003; Fang and Liang, 2005; Wang et al., 2004). The agreement for the retrieved *LAI* is generally good for the other biomes.

MGVI values are systematically lower than the other *fAPAR* estimates. Such disagreement with the neural network results was unforeseen as both *MGVI* and *fAPAR*-NN-MERIS derive from the same observations.

The three sites over which the temporal consistency was evaluated (Figure 3) show consistent dynamics between the NN-MERIS, MODIS and *MGVI*, products. Differences nevertheless arise for the Gourma site, for leaf production and senescence periods: the slopes of *LAI* growth and decrease are sharper for the *LAI*-NN than that inferred from MODIS. They may result from the fact that MODIS estimates derive from a temporal compositing and are provided weekly whereas NN-MERIS, even though smoothed temporally, are estimated daily. The main noticeable differences come from the relative levels of the estimated variables as previously mentioned. *LAI*-NN estimates are generally lower than the corresponding MODIS product. In all these cases, the joint variation of *LAI* and *fAPAR* is in agreement with our expectations of the vegetation cycle. For Larose, whereas the estimation error for *LAI* was expected to be more important as for the cases of dense canopies, it appears that the NN estimates are closer to the VALERI ground truth than the MODIS or *MGVI* products. The erratic temporal variations of the NN estimated variables before the temporal smoothing (circles on Figure 3) gives an appraisal of the estimation uncertainty. They are mainly attributed to changes in the radiometric signal due to atmospheric effects and variations in the observation geometry. They thus reveal the sensitivity of the NN algorithm to errors in atmospheric corrections or cloud detection. Here, the estimation uncertainty is relatively small as the points do not depart too much from the time composite values (grey line).

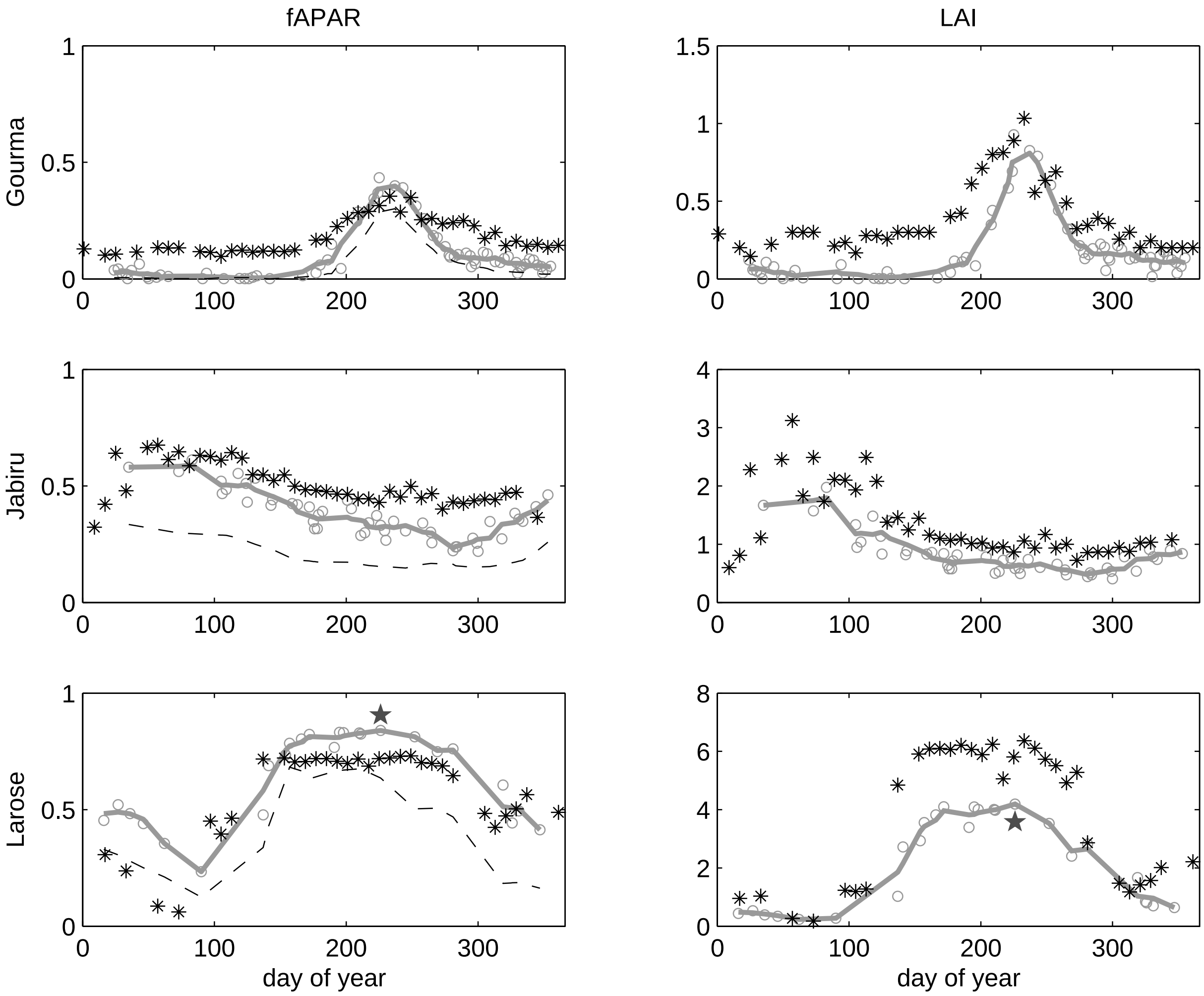

Figure 3: Examples of *fAPAR* (left) and *LAI* (right) time series for the Gourma (Mali, grassland), Jabiru (Australia, savanna), and Larose (Canada, mixed forest), sites. MODIS estimates are represented by stars (*);*MGVI* appears as a dashed line; original NN estimates before the temporal smoothing are represented by circles (o) while the time composite values are shown as the thick

grey line. The VALERI ground truth acquired the day 231 in Larose is represented by a pentagram (★).

5. Evaluation of the spatial consistency

The spatial consistency of the biophysical products inferred from a MERIS image was evaluated on an image acquired on October 20th, 2002 over the South-West of France and the Northern part of Spain (about 600x600 km²) (Figure 4). Water and obvious cloud pixels were flagged. The maps *fAPAR*, *LAI*, *fCover*, and *LAIxCab* estimated from MERIS show the same spatial structures (Figure 4d, e, f, g) with smooth spatial variations, and are very consistent with the biome classification map of the same region (Figure 4a). NN-MERIS estimates are also evaluated with respect to the monthly MODIS products at 1 km resolution (Figure 4b, c).

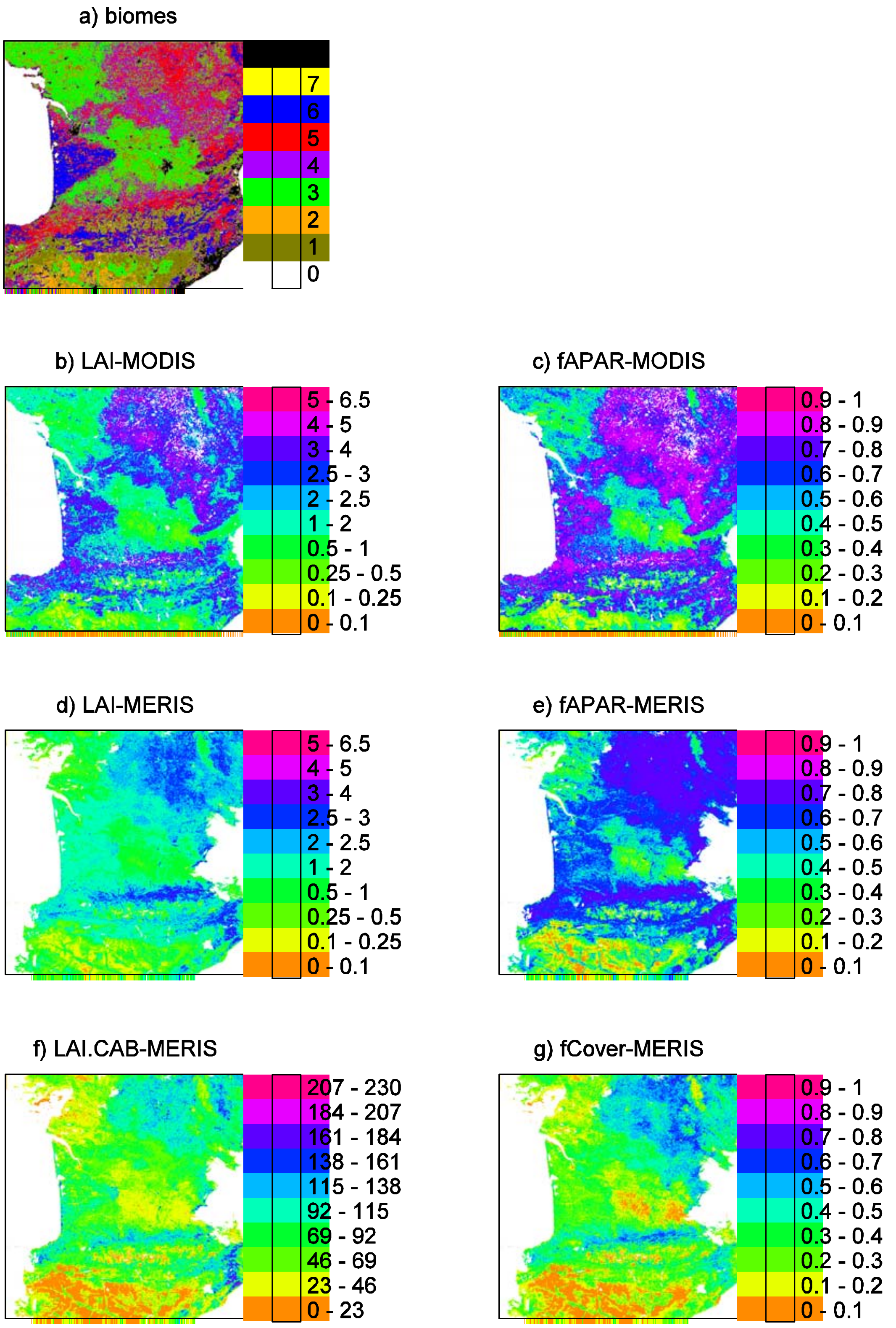

Figure 4: a) Biome classification map of the region covering South-West of France and North of Spain: 0) water, 1) grasses and cereal crops, 2) shrubs, 3) broadleaf crops, 4) savannas, 5) broadleaf forests, 6) needleleaf forests, 7) unvegetated areas, 8) urban areas. **b-c)** Corresponding monthly MODIS products of *LAI* and *fAPAR*. **d-g)** Maps of the NN-MERIS estimates of *LAI*, *fAPAR*, *LAIxCab* (μg.cm^{-2}), and *fCover*. The original MERIS image was acquired on the October 20th, 2002.

Generally, the lowest vegetation amounts (according to the retrieved values of the biophysical variables) are found for the areas covered with shrubs, grasses and cereal crops, and broadleaf crops. This is consistent with the acquisition date and the vegetation cycle, most of the agricultural crops being already harvested. The denser canopies correspond to pixels classified as savannas, and forests (broadleaf and needleleaf). The spatial structures of the *fAPAR* maps for NN-MERIS and MODIS are in good agreement, MODIS estimates being generally higher. Differences are more pronounced regarding the retrieved *LAI* values. They are generally greater for MODIS, especially for the forest pixels (as it has been previously noted), with common values above 4 up to 6.5. Such high leaf area density may be overestimated regarding to biome type and vegetation cycle. In comparison, the maximum *LAI* for NN-MERIS is 3.7. NN results retrieved over the Landes forest (needleleaf) reveal interesting features, likely highlighting algorithmic problems that should be corrected in the future. MODIS products exhibit for this region bordering the Atlantic shore (the blue triangle in Figure 4a) a rather high vegetation amount with *LAI* values typically between 3 and 5, and *fAPAR* values above 0.8. For the NN-MERIS estimates, *LAI* is in the 1.5-2.5 range while *fAPAR* varies in between 0.5 and 0.8; at the same time, estimated *fCover* values do not exceed 0.4. These results are likely not plausible and underestimate actual canopy characteristics. On another hand, these *LAI* estimates are consistent with ground measurements performed at the Nezer-VALERI site (located in the Landes) with a LAI2000 instrument in 2000 with a median measured *LAI* around 1.9. These results probably indicate that the leaf clumping (no clumping in SAIL and in the LAI2000 processing principles) may explain this feature.

6. Validation with respect to VALERI *in situ* measurements

Except for Concepcion and Fundulea, no MERIS observation is strictly concomitant with the ground measurements that were performed only once in 2003. The temporal shift is of 1 day for Barrax, 5 for Larose, 6 for Turco, and 14 for Haouz. Nevertheless, the time difference is small enough to assume that changes in the vegetation amount are small.

	grasses and cereal crops	**shrubs**	**broadleaf crops**	**savannas**	**broadleaf forests**	**needleleaf forests**
fAPAR	0.08	0.08	0.08	0.10	0.14	0.10
LAI	0.21	0.13	0.34	0.43	1. 43	1.66

Table 1 : Root Mean Square Error between NN-MERIS and MODIS estimates of *fAPAR* and *LAI* with respect to the biome type.

In all cases, NN-MERIS provides the best agreement with the VALERI in situ measurements (Figure 5). fAPAR and fCover values are well distributed around the 1:1 line whereas LAI values seem to slightly overestimate the ground truth for the surfaces with higher vegetation coverage. Such overestimation is also observed for LAI-MODIS for the Concepcion and Larose sites. As expected according to the previous findings, MGVI underestimates fAPAR-VALERI values. However, regarding to the limited number of validation points, it is difficult to draw definitive conclusions on the accuracy of the various estimation algorithms from this sole validation exercise. In particular, the lack of sites with high LAI values does not permit to evaluate the reliability of the approaches when the radiometric signal tends to saturate.

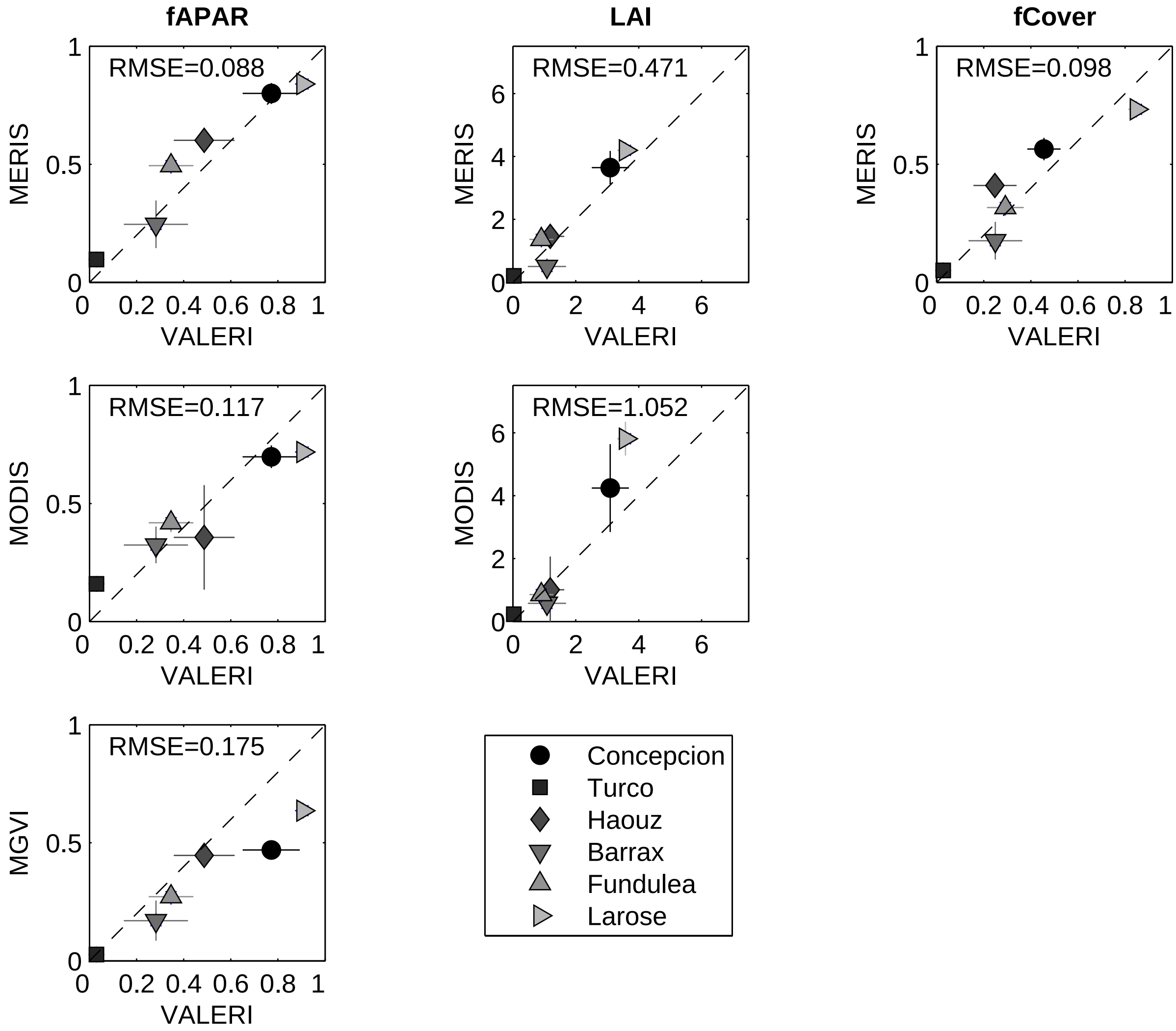

Figure 5: Validation of the NN-MERIS (top), MODIS (middle), and *MGVI* (bottom), biophysical products against VALERI ground truth. For the spaceborne estimates, the errorbars correspond to the standard deviation of the values estimated on the 3 x 3 pixels; for the *in situ* measurements, they correspond to the standard deviation of the 1km resolution data aggregated at 3 × 3 km².

7. Conclusion

A neural network algorithm for the estimation of canopy biophysical variables from MERIS imagery (at full and reduced resolutions) is proposed. It is designed to jointly estimate the leaf area index, the fraction of absorbed photosynthetically active radiation, the fractional vegetation cover and the canopy chlorophyll content, from a single observation, once provided the top of canopy reflectance measurements in 11 spectral bands and the geometry of observation. The network was trained on a synthetic dataset made of radiative transfer model simulations by the PROSPECT+SAIL models. Its estimation performances were evaluated with respect to MODIS (*LAI* and *fAPAR*) and *MGVI*-MERIS products on a selection of sites corresponding to various biome types and vegetation cycles. A systematic bias was found between the *MGVI* and the *fAPAR* retrieved from NN-MERIS and MODIS. On another hand, the results have shown a general good agreement between NN-MERIS and MODIS estimates for *LAI* and *fAPAR*. Nevertheless, NN-MERIS tends to retrieve lower *LAI* values than the MODIS algorithm for broadleaf and needleleaf forests. The validation of the remotely sensed variables over six VALERI sites sampled in 2003 revealed a remarkable estimation accuracy of the NN algorithm as compared to the other biophysical products. These findings are partly explained by the same definition of *LAI* (effective *LAI*) that is used both for the VALERI measurements and for the NN *LAI* product. To draw more reliable statistics on the actual estimation performances of the NN algorithm, it is mandatory to extend this validation exercise by using more sites and increasing the frequency of the *in situ* measurements to better monitor the vegetation cycles.

For the moment, the estimation reliability of biophysical variables from MERIS measurements is limited by the lack of an operational cloud filtering implemented within the processing chain. Important efforts should therefore be undertaken to solve this critical issue before accurate products can be produced and used operationally. Potential improvements of the current algorithm are also being investigated to increase its estimation performances. The MODIS algorithm is biome specific while our neural network one is not. The use of a generic NN, designed to evenly operate on any vegetation type, may has shown its limits here when applied on the Landes forest (needleleaves). The somewhat unrealistic estimates of the structural variables partly derive from the under-representation of the particular features of needleleaf canopies in the training process (distribution of the biophysical variables and adequacy of the radiative transfer simulations). The simple radiative transfer model, although proving quite efficient, could be replaced by a more realistic one where leaf clumping could be better accounted for. However, when defining the *LAI* as the effective one, the current simple radiative transfer seemed performing well. As the correction of the atmospheric effects is an important step of the estimation process, the possibility has been examined to couple atmosphere and canopy radiative transfer models for the training of the neural network. This would allow deriving biophysical variables directly from top of atmosphere observations. An improved version of the algorithm capitalizing on actual MERIS measurements is planed to better account for the uncertainties on variables and measurements-model.

8. References

Abuelgasim, A.A., Gopal, S., Strahler A.H. (1998). Forward and inverse modelling of canopy directional reflectance using a neural network, *International Journal of Remote Sensing*, 19(3): 453-471.

Atkinson, P.M., Tatnall, A.R.L. (1997). Neural networks in remote sensing, *International Journal of Remote Sensing*, 18(4): 699-709.

Atzberger, C. (2004). Object-based retrieval of biophysical canopy variables using artificial neural nets and radiative transfer models, *Remote Sensing of Environment*, 93: 53-67.

Bacour, C., Jacquemoud, S., Tourbier, Y., Dechambre, M., Frangi, J. P. (2002). Design and analysis of numerical experiments to compare four canopy reflectance models, *Remote Sensing of Environment*, 79: 72-83.

Baret, F., Fourty, T. (1997). Radiometric estimates of nitrogen status of leaves and canopies, in *Diagnosis of Nitrogen Status in Crops*, Lemaire G., (Eds), Springer-Verlag, Berlin, 201-227.

Baret F., Morisette, J., Fernandes, R., Champeaux, J.-L., Myneni, R.B., Chen, J., Plummer, S., Weiss, M., Bacour, C., Derive, G. (2006a). Evaluation of the representativeness of networks of sites for the global validation and inter-comparison of land biophysical products. Proposition of the CEOS-BELMANIP, *IEEE Transactions on Geoscience and Remote Sensing*, submitted

Baret, F., Weiss, M., Allard, D., Garrigues, S., Leroy, M., Jeanjean, H., Fernandes, R., Myneni, R.B., Privette, J.L., Morisette, J., Bohbot, H., Bosseno, R., Dedieu, G., Di Bella, C., Duchemin, B., Espana, M., Gond, V., Gu, X.F., Guyon, D., Lelong, C., Maisongrande, P., Mougin, E., Nilson, T., Veroustraete, F., Vintilla, R. (2006b). VALERI: a network of sites and a methodology for the validation of medium spatial resolution land satellite products, *Remote Sensing of Environment*, submitted.

Béal D., Baret F., Bacour C., Pavageau K., Gu X.-F. (2006). A method for aerosol correction from the spectral variation in the visible and near infrared. Application to the MERIS sensor, *International Journal of Remote Sensing*, submitted.

Buermann, W., Wang, Y., Dong, J., Zhou, L., Zeng, X., Dickinson, R.E., Potter, C.S., Myneni, R.B. (2002). Analysis of multiyear global vegetation index data set, *Journal of Geophysical Research*, 107(D22): 4646.

Campbell, G. S. (1990). Derivation of an angle density function for canopies with ellipsoidal leaf angle distribution, *Agricultural and Forest Meteorology*, 49:173–176.

Cohen, W.B., Maiersperger, T.K., Yang, Z., Gower, S.T., Turner, D.P., Ritts, W.D., Berterretche, M., Running, S.W. (2003). Comparisons of land cover and LAI estimates derived from ETM+ and MODIS for four sites in North America: a quality assessment of 2000/2001 provisional MODIS products, *Remote Sensing of Environment*, 88: 233-255.

Combal, B., Baret, F., Weiss, M., Trubuil, A., Macé, D., Pragnère, A., Myneni, R., Knyazikhin, Y., Wang, L. (2002). Retrieval of canopy biophysical variables from bi-directional reflectance. Using prior information to solve the ill-posed inverse problem, *Remote Sensing of Environment*, 84: 1-15.

Chen, J. M., Pavlic, G., Brown, L., Cihlar, J., Leblanc, S. G., White, H. P., Hall, R. J., Peddle, D.R., King, D.J., Trofymow, J.A., Swift, E., Sanden, J.V.D., Pellikka, P.K.E. (2002). Derivation and validation of Canada-wide coarse-resolution leaf area index maps using high-resolution satellite imagery and ground measurements, *Remote Sensing of Environment*, 80:165-184.

Danson, F.M., Rowland, C.S., Baret F. (2003). Training a neural network with a canopy reflectance model to estimate crop leaf area index, *International Journal of Remote Sensing*, 24(23): 4891-4905.

Daughtry, C.S.T., Walthall, C.L., Kim, M.S., Brown de Costoun, E., McMurtrey III, J.E. (2000) Estimating corn leaf chlorophyll concentration from leaf and canopy reflectance, *Remote Sensing of Environment*, 74: 229-239.

Derive, G., Bacour, C., Baret, F., Béal, D., Weiss, M., Bicheron, P., Lacaze, R., Leroy, M., Champeaux, J.-L., Masson, V., Roujean, J.-L. (2003). CYTTARES: a global database for the training and inter-comparison of biophysical products derived from medium resolution sensors, *In proceedings 2003 IEEE International Geoscience and Remote Sensing Symposium, Toulouse (France), 21 - 25 July*, 3 pp.

Fang, H., Liang, S. (2005). A hybrid inversion method for mapping leaf area index from MODIS data: experiments and application to broadleaf and needleleaf canopies, *Remote Sensing of Environment*, 94: 405-424.

Fourty, T., Baret F. (1997), Amélioration de la précision des coefficients d'absorption spécifique de la matière sèche et des pigments photosynthétiques. Avignon, INRA Bioclimatologie: 35.

Gobron N., Pinty, B., Verstraete, M., Govaerts, Y. (1999). The MERIS global vegetation index (MGVI): description and preliminary application, *International Journal of Remote Sensing*, 20(9): 1917-1927.

Gross, L., Thiria, S., Frouin, R., Mitchell, B.G. (2000). Artificial neural networks for modeling the transfer function between marine reflectance and phytoplankton pigment concentration, *Journal of Geophysical Research*, 105(C2): 3483-3495.

Holben, B.N., Eck, T.F., Slutsker, I., Tanré, D., Buis, J.P., Setzer, A., Vermote, E., Reagan, J.A., Kaufman, Y.F., Nakajima, T., Lavenu, F., Jankowiak, I., Smirnov, A. (1998). AERONET-A federal instrument network and data archive for aerosol characterization, *Remote Sensing of* Environment, 66: 1-16.

Jacquemoud, S., Baret, F. (1990). PROSPECT: a model of leaf optical properties spectra, *Remote Sensing of Environment,* 34: 75-91.

Kimes, D.S., Nelson, R., Manry, M.T., Fung, A.K. (1998). Attributes of neural networks for extracting continuous vegetation variables from optical and radar measurements, *International Journal of Remote Sensing*, 19(14): 2639-2663.

Kimes, D.S., Knyazikhin, Y., Privette, J.L., Abuelgasim, A.A., Gao, F. (2000). *Inversion methods for physically-based models*, *Remote Sensing Reviews*, 18: 381-439.

Knyazikhin, Y., Martonchik, J.V., Diner, D.J., Myneni, R.B., Verstraete, M., Pinty B., Gobron N. (1998a). Estimation of vegetation canopy leaf area index and fraction of absorbed photosynthetically active radiation from atmosphere-corrected MISR data, *Journal of Geophysical Research*, 103(D24): 32239-32256.

Knyazikhin, Y., Martonchik, J.V., Myneni, R.B., Diner D.J., Running S.W. (1998b). Synergistic algorithm for estimating vegetation canopy leaf area index and fraction of absorbed photosynthetically active radiation from MODIS and MISR data, *Journal of Geophysical Research*, 103(D24): 32257-32276.

Krasnopolsky, V.M., Chevallier, F. (2003). Some neural network applications in environmental sciences. Part II: advancing computational efficiency of environmental models, *Neural Networks*, 16: 335-348.

Kuusk, A. (1991). The hot spot effect in plant canopy reflectance, , *in Photo-vegetation interactions, Applications in Optical Remote Sensing and Plant Ecology*, Myneni R.B. and Ross J.R. (Eds), Springer Verlag, Berlin, 139-159.

Lacaze, R. (2005). POLDER-2 land surface level-3 products user manual. Algorithm description and product validation, available at *http://smsc.cnes.fr/POLDER/SCIEPROD/P2-TE3-UserManual-I1.40.pdf*, 71 pp.

Liu, W., Baret, F., Gu, X., Zhang, B., Tong, Q., Zheng, L. (2003). Evaluation of methods for soil surface moisture estimation from reflectance data, *International Journal of Remote Sensing*, 24(10): 2069-2083.

Morisette, J., Baret, F., Privette, J.L., Myneni, R.B., Nickeson, J., Garrigues, S., Shabanov, N., Weiss, M., Fernandes, R., Leblanc, S., Kalacska, M., Sanchez-Azofeifa, G.A., Chubey, M., Rivard, B., Stenberg, P., Rautiainen, M., Voipio, P., Manninen, T., Pilant, D., Lewis, T., Iiames, J., Colombo, R., Meroni, M., Busetto, L., Cohen, W., Turner, D., Warner, D., Petersen, G.W., Seufert, G., Cook, R. (2006). Validation of global moderate resolution LAI Products: a framework proposed within the CEOS Land Product Validation subgroup, *IEEE Transactions on Geoscience and Remote Sensing*, in press.

Rahman, H., Dedieu, G. (1994). SMAC: a simplified method for the atmospheric correction of satellite measurements in the solar spectrum, *International Journal of Remote Sensing*, 15(1): 123-143.

Rast, M., Bézy, J.-L., Bruzzi, S. (1999) The ESA Medium Resolution Imaging Spectrometer MERIS -a review of the instrument and its mission, *International Journal of Remote Sensing*, 20: 1682-1701.

Smith, J. A. (1993). LAI inversion using a back-propagation neural network trained with a multiple scattering model, *IEEE Transactions on Geoscience and Remote Sensing*, 31, 1102–1106.

Verhoef, W. (1984). Light scattering by leaf layers with application to canopy reflectance modeling: the SAIL model, *Remote Sensing in Environment*, 16:125-141.

Verhoef, W. (1985). Earth observation modeling based on layer scattering matrices, *Remote Sensing in Environment*, 17:165-178.

Viovy, N., Arino, O., Belward, A.S. (1992). The Best Index Slope Extraction (BISE): A method for reducing noise in NDVI time-series., International Journal of Remote Sensing, 13(8): 1585-1590.

Wang, Y., Woodcock C.E., Buermann, W., Stenberg, P., Voipio, P., Smolander, H., Häme, T., Tian, Y. Hu., J., Knyazikhin, Y., Myneni, R.B. (2004). Evaluation of the MODIS LAI algorithm at a coniferous forest site in Finland, *Remote Sensing in Environment*, 91: 114-127.

Weiss, M., Baret, F., (1999). Evaluation of canopy biophysical variable retrieval performances from the accumulation of large swath satellite data, *Remote Sensing of Environment*, 70:293-306.

Zarco-Tejada, P.J., Miller, J.R., Morales, A., Berjón, A., Agüera, J. (2004). Hyperspectral indices and model simulation for chlorophyll estimation in open-canopy tree crops, Remote Sensing of Environment, 90: 463-476.

Zurita-Milla, R., Clevers, J. Schaepman, M., Kneubuehler, M., (2006). Effects of MERIS L1b radiometric calibration on regional land cover mapping and land products, *International Journal of Remote Sensing*, submitted.