Vegetation and biochemical indices retrieved from a multitemporal AVIRIS data set

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ABSTRACT

An analysis, based on the inversion of a simple non-linear model of the ground reflectance, was conducted on several AVIRIS scenes. The scenes were acquired during the MAC EUROPE 91 campaign on the 5th and 22nd of July, over two test sites (Black Forest and Freiburg). The model consists in a linear mixing of the soil reflectance and a green vegetation reflectance described with a Kubelka-Munk formula containing the chlorophyll a+b and water specific absorption coefficients. Its inversion provides a Green Vegetation Fraction (GVF) of the pixel and two parameters related respectively to chlorophyll (a_{chl}) and water (a_w). The model can then be used to evaluate the magnitude of the 1.7 μm absorption feature which is thought to be a signature of the vegetation biochemical components. The spatial and temporal variability of this feature over the scenes is commented.

1. INTRODUCTION

Estimating the leaf biochemical components (photosynthetic pigments, water, lignin, cellulose...) from high spectral resolution data is a challenge for the coming years. Many studies (Goetz et al., 1990; Jacquemoud and Baret, 1990; Curran et al., 1992...) showed the prospect of succeeding in this task at the leaf level. Nevertheless, a vegetation canopy is not a large leaf and results obtained at the leaf level may not be suitable at the canopy level. There are mainly two strategies to estimate the canopy biochemistry: the use of statistical relationships and the use of models. The first method allowed Peterson et al. (1988) and Wessman et al. (1989) to map lignin and nitrogen on temperate forests with AIS data. The second one is relatively new and promising: it consists in modeling the canopy spectral reflectance and in inverting the model in order to retrieve the vegetation characteristics. In this way, a spectral matching technique has been applied by Gao and Goetz (1990, 1992) with a very simple model to the 1.5-1.74 μm region of AVIRIS spectra. These authors demonstrated that the vegetation spectrum in this wavelength region consists of the spectral component of liquid water and spectral components of dry vegetation material. Recently, Jacquemoud and Baret (1993) attempted to invert a leaf+canopy radiative transfer model on vegetation spectra in order to estimate the chlorophyll a+b concentration as well as the equivalent water thickness. An operational use of this approach requires a compromise between simple equations that cannot take into account the multiple scattering due to canopy architecture (distortion of the biochemical signal), and complex models whose inversion is tricky and time consuming.

The main purpose of this paper is to test the possibility of inverting a non-linear model of ground reflectance on AVIRIS scenes containing both forested areas and several types of agricultural fields. In this simple model, we first separate the soil fraction from the green vegetation fraction which is described by a Kubelka-Munk formula for an optically thick medium. Chlorophyll and water are taken into account by using their respective specific absorption coefficients gleaned in the literature. The temporal variability of the suspected biochemical signature is also examined as scenes were acquired on the same test sites at about two weeks interval.

In Proc 25th International Symposium on Remote Sensing and Global Environmental Change, Graz (Austria), 4-8 April 1993, pp. 273-281.

2. TEST SITE DESCRIPTION

In the frame of the MAC Europe'91 campaign, AVIRIS overflights have been performed on the 5th and 22nd of July over two test sites in the southern part of Germany. An extensive ground truth measurement campaign was set up to accommodate the airborne measurements. Unfortunately, not all of the collected ground reflectance data have been available for our studies.

The agricultural study area is situated approximately 20 km West of the City of Freiburg in the Upper Rhine Valley and has an extension of 6 × 4 km. This test site contains both forested areas (19%) and agricultural areas (50%). The agricultural part is intensively cultivated with the main crops being wheat, corn, barley, potatoes, sugar beet, and vine. The average field size of approximately 1.5 ha is representative for small scale European farming. The area is topographically flat at an altitude of 200 m above sea level. The soils are dominated by the quarternary sediments of the Rhine River and thus show a great variety of grain size distribution and high porosity. The latter accompanied by low clay contents results in high infiltration rates requiring the irrigation of the intensive cultivation areas of corn.

The Black Forest test site is located near the town of Villingen/Schwennigen at an altitude ranging from 800 to 960 m above sea level. Beside some small areas covered by Scots pine (*Pinus silvestris* L.) and silver fir (*Abies alba* Mill.), the dominant tree specie of the overall region is Norway spruce (*Picea abies*) with tree ages from 80 to 120 years and tree heights from 30 to 40 m. The understory is mainly composed of blueberries and of young spruce and fir trees for rejuvenation. Soils are dominated by sandy-loamy acid brown earths.

3. MODELING LEAF SPECTRA

Although canopy reflectance characteristics cannot be fully explained by leaf reflectance properties, the main connection between the changes in the biochemical content of a canopy and the radiative transfer from a canopy is through changes in the spectral properties of the leaf (Peterson, 1991). The overall shape of a leaf reflectance spectrum can be explained by the absorption features of chlorophyll and water, once they are included in a radiative transfer model. A number of simple models exist which describe the scattering in various ways: Kubelka-Munk (Allen and Richardson, 1968), plate models (Jacquemoud and Baret, 1990), stochastic model (Tucker and Garratt, 1977), among others. They are successful in reproducing the major shapes of a leaf reflectance (or transmittance) spectrum such as the photosynthetic pigments absorption peaks from the visible region up to the red edge transition, and the water absorption peaks in the middle infrared. However, there are details in the spectrum which are still unaccounted for, such as a small absorption feature centred around 1.7 μm. An increasing interest is being brought to this feature as it is thought to be a signature of biochemicals such as lignin, cellulose, starch and proteins. In the frame of spectral unmixing studies, Smith et al. (1990) have revealed a systematically recurring residual; it has also been directly investigated using spectral matching techniques (Goetz et al., 1990).

We are presently working on radiative transfer models which explicitly include the leaf biochemical components. These biochemicals are introduced by considering each of their contribution in the spectral absorption coefficient of the leaf tissue. It is not the purpose of this paper to present this work which has not yet reached its conclusions. However, the studies conducted so far on laboratory spectra have shown :

- that the 1.7 μm feature cannot be explained by water alone,
- that it cannot be reproduced by using the specific absorption coefficient spectra available today for lignin (wood), cellulose, starch or proteins,
- that the model based on chlorophyll and water can reproduce accurately the spectrum in some spectral regions where these two components dominate the absorption (from 0.5 to 0.73 μm and from 1.5 to 1.65 μm respectively),
- that the amplitude of the 1.7 μm residual is dependent on the type of vegetation: thus in Figure 1, one can notice that the residual is higher for the spruce needles than for the other plant leaves.

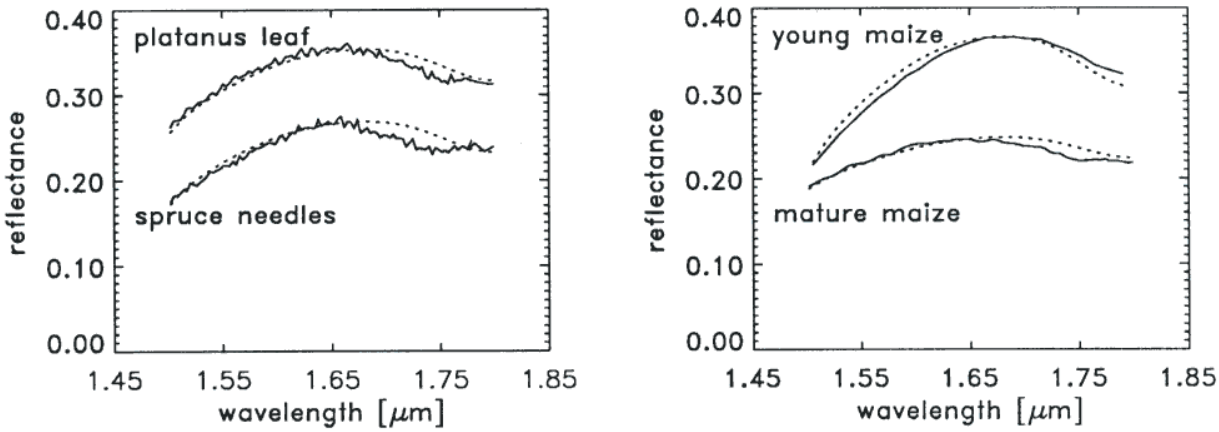

Figure 1: Laboratory reflectance spectra of various types of vegetation in the 1.5-1.8 μm spectral window (—) and how they are fitted with a radiative transfer model including only the absorption coefficient of pure water (**…**).

Ultimately, our purpose is to couple a leaf optical properties model with a canopy reflectance model, and to perform the inversion on imaging spectrometry spectra. This is a long-term job. In order to document the feasibility and the interest of such a procedure, we will consider a simplified model based on the Schuster-Schwarzschild ("two flow") approximation of the radiative transfer equation (Chandrasekhar, 1960). In that case, the complexity of the optimization algorithm is drastically reduced, and the inversion procedure is conceivable on an AVIRIS cube.

4. PROCESSING OF AVIRIS DATA

The first task is to correct the image from the atmospheric effects. The surface reflectance is obtained from the radiance by using the "Atmosphere Removal Program" developed at the CSES/CIRES/University of Colorado (Gao and Goetz, 1990). This program uses the 5S code to model the aerosols while the gaseous transmittance calculation allows for one pixel to another variable amount of atmospheric water vapor. The amount of water vapor is obtained from the intensity of the absorption lines at 0.94 and 1.14 μm. Figure 2 shows off typical reflectance spectra derived from this procedure. It can be seen that the near infrared plateau is still much disturbed by remains of the water vapor features; such an effect would be typically produced by a slight error in the wavelength calibration. This is of little importance for this study as it does not make use of the NIR plateau region.

As the AVIRIS scenes contained both forested areas with a high vegetation cover and agricultural fields of which some have a low cover, the analysis had to take into account the soil reflectance. This was done in the simplest way by assuming a linear mixing of soil and vegetation spectra; we therefore write:

$$R_p(\lambda) = a_s . R_s(\lambda) + a_v . R_v(\lambda) \tag{1}$$

where $R_p(\lambda)$ is the reflectance of the pixel, $R_s(\lambda)$ is the soil reflectance, $R_v(\lambda)$ is the vegetation reflectance, a_s and a_v are the corresponding abundances in the pixel spectrum. The soil spectrum was taken from the image as the mean spectrum of a small area known to be bare soil, and assumed to be representative of the scene. The vegetation spectrum was modeled with a Kubelka-Munk formula adapted for an optically thick homogeneous medium:

$$R_v(\lambda) = \frac{2 - \omega_0(\lambda) - 2.\sqrt{1 - \omega_0(\lambda)}}{\omega_0(\lambda)} \tag{2}$$

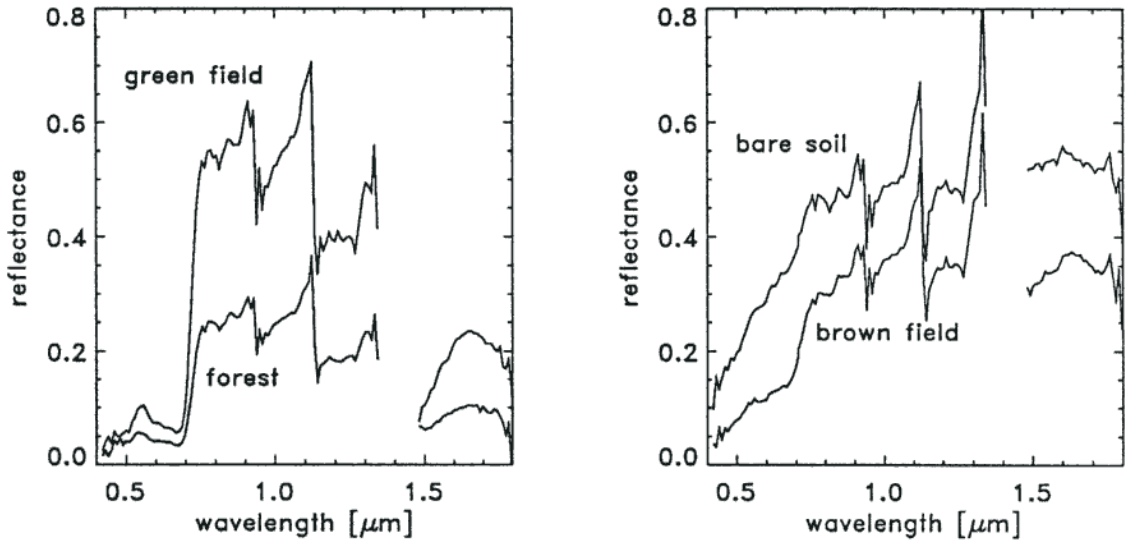

Figure 2: Examples of single pixel AVIRIS reflectance spectra after the atmospheric correction using the Atmosphere Removal Program.

$$\omega_0(\lambda) = \frac{s}{s + k(\lambda)} = \frac{1}{1 + \frac{k(\lambda)}{s}} \tag{3}$$

where $\omega_0(\lambda)$ is the single scattering albedo of the medium, $k(\lambda)$ its absorption coefficient, and s its scattering coefficient. As the diffusion phenomena inside leaf tissues are mainly due to multiple reflections and refractions, s can reasonably be assumed to be wavelength independent. Allen and Richardson (1968) also described the interaction of light with a plant canopy with the Kubelka-Munk theory; one must however highlight that the scattering coefficient defined by these authors (let note s') is in fact a backscattering coefficient which differs from the the scattering coefficient by a factor two: $s = 2 \times s'$. Equation 2 depends on the definition adopted. Regarding the absorption in vegetation, we assume that it is mainly due to chlorophyll and water and write:

$$\frac{k(\lambda)}{s} = \frac{1}{s}.(c_{chl}.k_{chl}(\lambda) + c_w.k_w(\lambda)) = a_{chl}.k_{chl}(\lambda) + a_w.k_w(\lambda) \tag{4}$$

where $k_{chl}(\lambda)$ is the specific absorption coefficient of chlorophyll a+b expressed in $cm^2.\mu g^{-1}$, $k_w(\lambda)$ is the specific absorption coefficient of water expressed in cm^{-1} (we used for chlorophylls the *in vivo* absorption coefficient of Jacquemoud and Baret (1990) and the measurements of Curcio and Petty (1951) for water), c_{chl} is the chlorophyll concentration expressed in $\mu g.cm^{-2}$, and c_w is the equivalent water thickness expressed in cm. Finally, a_{chl} and a_w defined as the above concentrations divided by the scattering coefficient are the independent parameters of the vegetation spectrum model.

By combining formula (1), (2), (3) and (4), one obtains a model of the pixel reflectance as a non-linear function of four parameters, a_s, a_v, a_{chl}, and a_w: these parameters have been determined by least mean square fitting on the AVIRIS pixel reflectance by using a Marquardt algorithm (Marquardt, 1963). Two spectral windows were used in the fitting: the region ranging from 0.5 to 0.73 μm and that from 1.5 to 1.65 μm where the chlorophyll and water absorptions are respectively dominant. Once the fitting is performed, we can compute a "Green Vegetation Fraction" of the pixel, defined by:

$$GVF = \frac{a_v}{a_v + a_s} \tag{5}$$

We also retrieve a measured spectrum of the green vegetation fraction $R_{vm}(\lambda)$:

$$R_{vm}(\lambda) = \frac{R_p(\lambda) - a_s . R_s(\lambda)}{a_v} \tag{6}$$

Assuming that the 1.7 μm feature is an absorption due to a component of vegetation, we logically evaluate its magnitude from the absorptance corresponding to the measured (A_{vm}) and fitted vegetation spectra (A_v). The absorptance has been defined in this study as k/s and obtained by combining equations (2) and (3):

$$A(\lambda) = \frac{(R(\lambda)+1)^2}{4.R(\lambda)} - 1 \tag{7}$$

The residual has then been evaluated in the 1.65 to 1.76 μm spectral interval as:

$$res = \frac{1}{N} \sum (A_{vm} - A_v) \tag{8}$$

where the average is taken on the N AVIRIS channels in this spectral window. In addition, several vegetation indices such as the the NDVI (Normalized), the MSI (Moisture Stress Index),...etc have been computed. This analysis procedure was applied to four AVIRIS scenes (the Black Forest the Freiburg test sites on two dates). The processing of one scene took about 8 hours of computing time on a SUN SPARC 10 workstation.

5. RESULTS

Figure 3 shows that the above model can reproduce very well the spectra of the vegetated areas: the mean relative deviation ($\Delta R/R$) between the measured and modeled pixel reflectance spectra is typically of the order of 0.05 within the fitting windows.

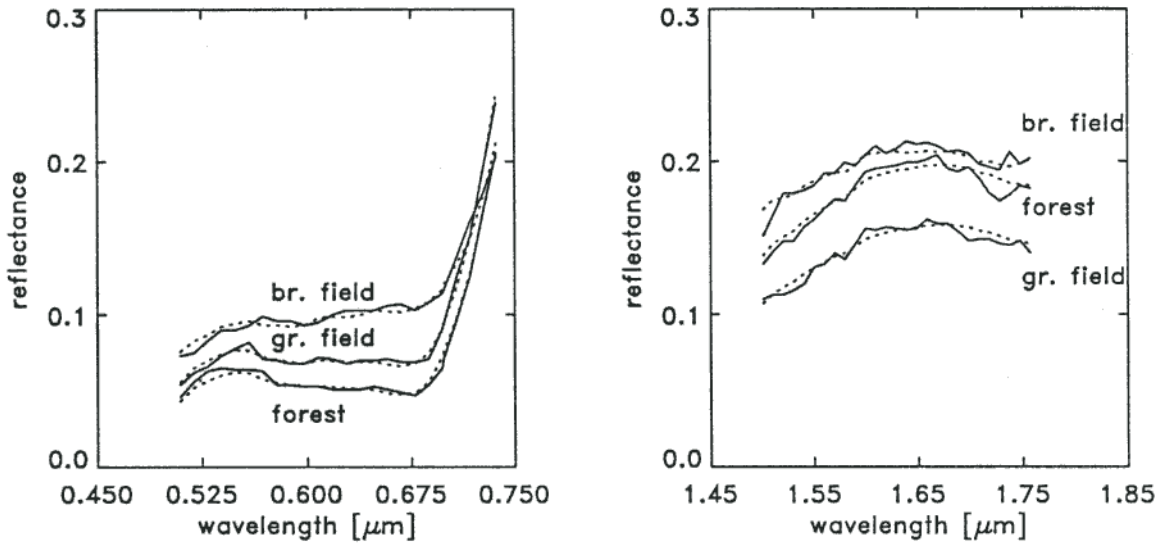

Figure 3: Comparison between single pixel AVIRIS reflectance spectra measured (—) and simulated (**…**) in the two windows used for the model inversion.

The results of the analysis performed on a part of the Freiburg test site, which contains both forested surfaces (2 large areas at the top/right part and a smaller one in the right corner of the image) and agricultural units, are gathered in Figures 4 and 5. The rectangular area in the top left corner of the image is a small lake; a small town is located in the centre of the image. The images in the left column of the figures represent processed AVIRIS data from the overflight of the 5th of July; the right column of the 22nd of July. By comparing the images from the two overflights a number of qualitative comments can already be made, but a detailed interpretation will only be possible by the confrontation with ground data, which are at the moment not available.

Over the forested regions, all the calculated indices and parameters are very stable from one overflight to the other; this was to be expected as a forest does not change significantly within a two week period. On the contrary, all the parameters calculated on the agricultural units reflect the growing and harvesting cycle of vegetation. Compared with the vegetation indices NDVI and MSI, the chlorophyll and water parameter (a_{chl} and a_w) demonstrate a higher sensitivity to the growing process. However, the interpretation of these two parameters is difficult as the hypothesis of the model to have an optically thick canopy probably does not hold on the fields. The image of the Green Vegetation Fraction seems to contain essentially the same information as the NDVI image although showing a better dynamics with respect to the cover type.

Major emphasis has been placed on the residual image in the spectral region of 1.7 µm because different biochemical components like lignin and cellulose have absorption features near this wavelength region. While prediction of the vegetation spectral reflectance by the model does not vary significantly in accuracy with wavelength in the other spectral domains, the residual seems to be higher around 1.7 µm, specially in the case of the forest spectrum (Figure 3). This is strengthened by Figure 5 where it is obvious that this residual clearly discriminates between forest and other types of vegetation. Within the forest, the spatial variability of the residual is clearly correlated with that of the Moisture Stress Index MSI (negative correlation) and the water parameter a_w (positive correlation). The situation is more complex regarding the agricultural units within the test site. By comparing the two residual images, several fields appear brighter (higher residual) on the 22nd of July, which could be related to the maturation of the different crops. A definite interpretation (taking into account the very low values of the residual) will only be possible by comparing these images with the agricultural and meteorological data of the local authorities.

A comparison of the AVIRIS images of the Black Forest test site revealed no significative differences between the two overflights regarding the calculated vegetation indices and parameters. Of major interest are three well documented plots within this forest, of which two have been fertilised with ammonium sulphate of different concentrations for the last three years. According to our analysis eventual effects of the fertilisation on canopy characteristics like chlorophyll concentration, water content and the biochemical components in the 1.7 µm region were not detectable.

6. CONCLUSION

At this point of the study, we can conclude that the 1.7 µm residual does show a systematic relation with the vegetation cover type. It is markedly higher on forests than on agricultural crops and significantly varies within the forest. In this respect, the results obtained on two different test sites and two dates are reproducible. On the fields, the variability is very faint and partly obscured by the uncertainties resulting from the detector noise. Progress in the interpretation of this spectral feature needs further work both by confronting the remotely sensed data with ground information and by performing accurate and systematic measurements in the laboratory.

This work has also shown the possibility of inverting non-linear models of the green vegetation spectrum on imaging spectrometer data. Although the model used is excessively simple, it contains explicitly the effect of the two main components which are chlorophyll and water, and is able to describe accurately the spectrum shape in two spectral windows. This result is encouraging to pursue this approach by using more detailed models which will

make use of the entire spectrum and will provide parameters more easily interpretable in terms of the canopy characteristics.

7. REFERENCES

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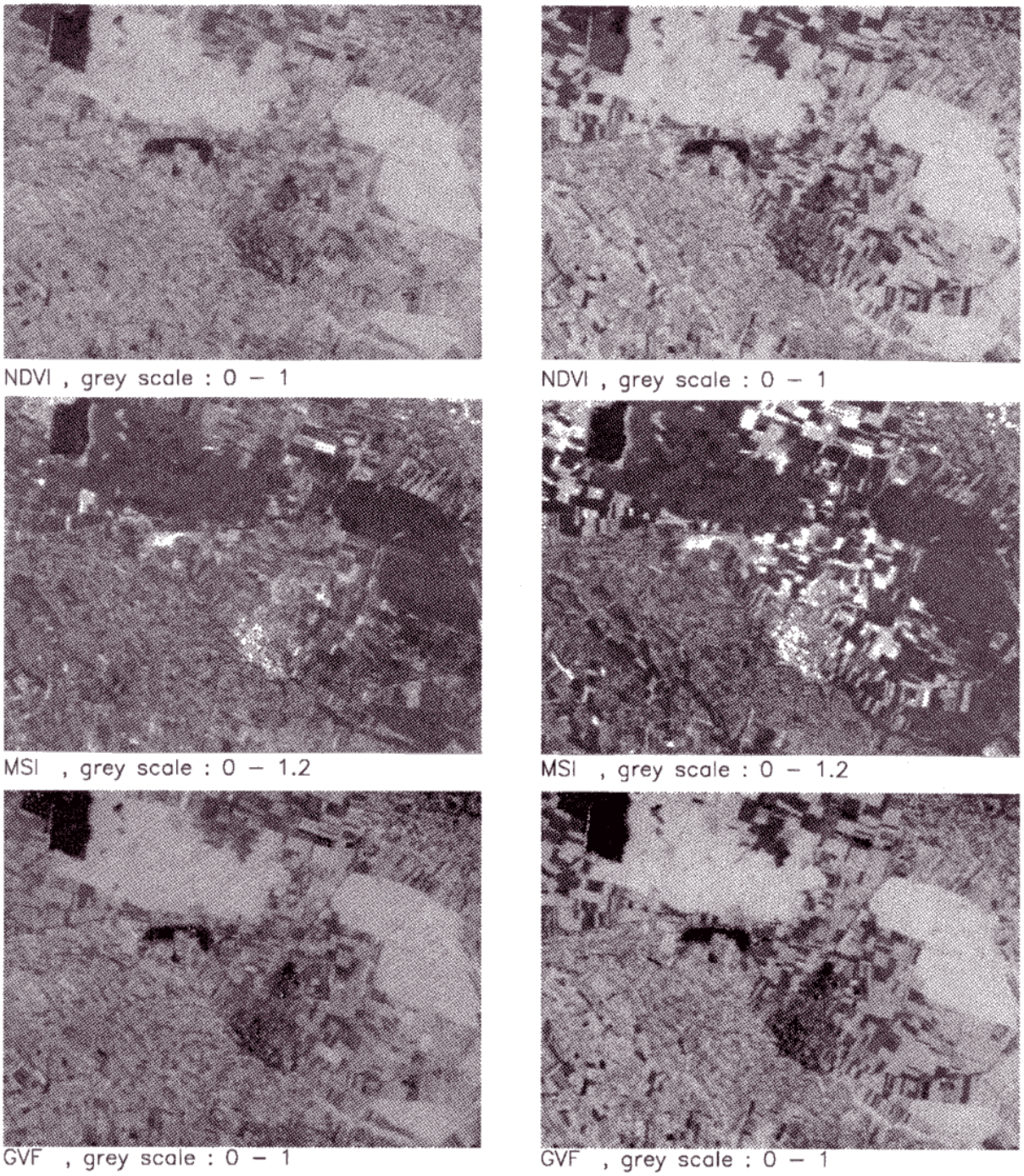

Figure 4: NDVI, MSI and the Green Vegetation Fraction (GVF) represented over a fraction of the Freiburg test site for the two dates; left column is on the 5th of July, right column on the 22nd of July.

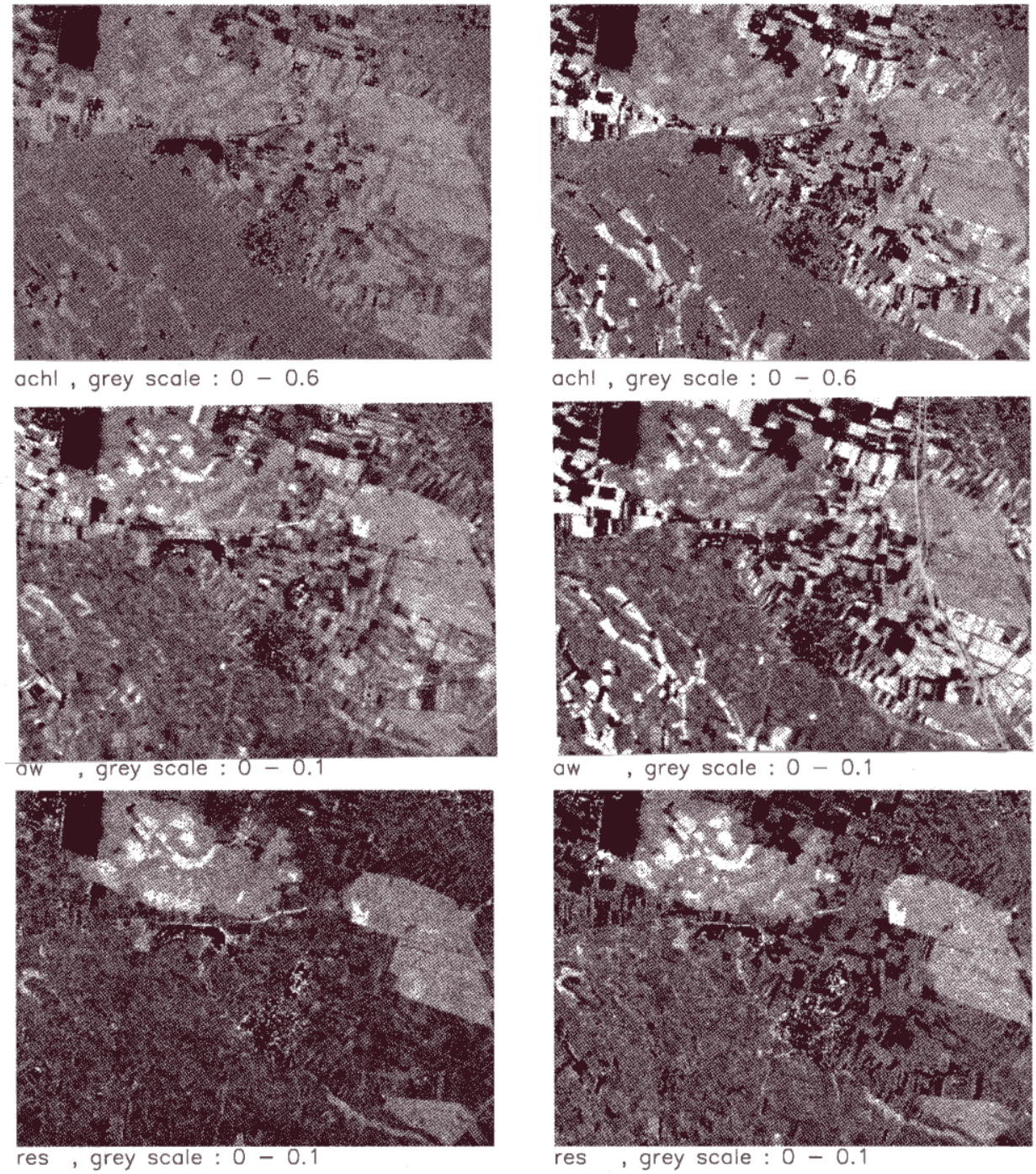

Figure 5: The chlorophyll (a_{chl}) and water (a_w) parameters together with the 1.7 μm residual (res) represented over a fraction of the Freiburg test site for the two dates; left column is on the 5th of July, right column on the 22nd of July.