Leaf pigment retrievals from DAISEX data for crops at BARRAX: Effects of sun-angle and view-angle on inversion results

John R. Miller[1,2], Jose Moreno[3], Pablo J. Zarco-Tejada[4], Luis Alonso[3] and Driss Haboudane[2]

1) Department of Physics and Astronomy, York University, 4700 Keele St., Toronto, Ontario, M3J 1P3, Canada jrmiller@yorku.ca
2) Centre for Research in Earth and Space Science (CRESS), Petrie Science Building, York University, 4700 Keele St., Toronto - Ontario M3J 1P3, Canada, driss@terra.phys.yorku.ca
3) Department of Thermodynamics, Faculty of Physics, University of Valencia, Dr. Moliner 50, 46100 Burjassot, Valencia, Spain
4) Grupo de Óptica Atmosférica (GOA-UVA), Escuela Técnica Superior de Ingenierías Agrarias, Campus de La Yutera, Universidad de Valladolid, Avda. de Madrid, 44, Palencia, 34004 Spain, pzarco@iaf.uva.es

ABSTRACT-*The use of combined leaf and canopy models to retrieve biophysical crop variables are increasingly thought to provide an effective means of providing quantitative input needed to determine stress condition and improve crop yield predictions based on physiological condition. Nevertheless, the sensitivity of such retrieval results to changes in view and sun angle are needed if efficient single-view optical image data are to attain operational agriculture use. Although some studies have been carried out using synthetic model data, similar studies using real data have been very limited due to the unavailability of such data sets. In this research the focus is on the retrieval of leaf pigment (chlorophyll a+b). Some recent studies have demonstrated model-based retrievals of leaf chlorophyll with RMSEs <5 $\mu g/cm^2$ by comparison with field sampling and subsequent laboratory chemical analysis. The research reported here uses the extensive DAISEX data set acquired at Barrax, Spain in 1999 and 2000. Airborne data collection strategies provided DAIS, ROSIS and HyMap hyperspectral data in which various field study plots have been observed under widely varying view angles and also at significantly different solar zenith angle. Nearly simultaneously, a comprehensive field data set was acquired on specific crop plots which provided measurements of the following relevant crop variables among others: LAI, percent vegetation cover, leaf chlorophyll content, biomass, leaf and canopy water content, and soil reflectance. We use a combined modeling and indices-based approach, which predicts the leaf chlorophyll content while minimizing LAI influence and underlying soil effects. The sensitivity of leaf chlorophyll predictions with changes in view and sun angle are reported and analyzed through modeling studies for a range of plots in the DAISEX data set.*

1 INTRODUCTION AND BACKGROUND

Recent research activities have focused on understanding the relationships between vegetation optical properties and photosynthetic pigment concentrations within green leaf tissues, namely: chlorophyll a, chlorophyll b, and carotenoids. Various approaches are being developed to estimate the chlorophyll content both at the leaf and canopy scales. Generally, these use some combination of empirical and semi-empirical methods and canopy model inversions (Gitelson et al., 1996; Blackburn, 1999; Datt, 1999; Daughtry et al., 2000; Demarez and Gastellu-Etchegorry, 2000; Zarco-Tejada et al., 2001). Amongst these investigations, there are studies of optical indices for chlorophyll estimation, which focus on evaluating the reflectance in individual narrow bands, band reflectance ratios and combinations, and the characteristics of derivative spectra. Attention is paid to identify different combinations of spectral bands to minimize variations arising from other confounding factors and to maximize sensitivity to chlorophyll content. Their concept and formalism are based on the relationships existing between chlorophyll concentrations and some specific narrow spectral bands. The spectral regions that are identified as the most suitable to chlorophyll effects study are those around 680 nm, corresponding to absorption peak of chlorophyll a, and 550 nm matching with the minimum chlorophyll absorption in the visible domain. Some recent studies (Haboudane et al., 2002) have demonstrated model-based retrievals of leaf chlorophyll a+b (denoted Chl a+b, below) using airborne imaging spectrometers data over agriculture crops with RMSEs <5 mg/cm^2 by comparison with field sampling and subsequent laboratory chemical analysis. For the research results reported in this paper we have used the Haboudane et al. (2002) approach for pigment retrieval on the extensive DAISEX data set acquired at Barrax, Spain in 1999 and 2000. Airborne data collection strategies provided DAIS, ROSIS and HyMap hyperspectral data in which various field study plots have been observed under varying view angles and also at significantly different solar zenith angles. This has allowed preliminary conclusions on the effect of sun/view angles on leaf pigment retrievals.

2 LEAF CHLOROPHYLL a+b CONTENT RETRIEVAL APPROACH

The approach adopted for retrieval of leaf chlorophyll a+b content in this study, appropriate to agricultural crops throughout the growing season was that of as Haboudane et al. (2002), reviewed briefly below. To develop this methodology forward simulations at a 5 nm spectral interval were conducted with the turbid medium SAILH canopy model (Verhoef, 1984; Kuusk, 1985) coupled to the PROSPECT leaf model (Jacquemoud and Baret, 1990) for LAI values (0.1 to 8), 12 leaf chlorophyll content (5 to 60 μg/cm^2), and three sun zenith angles (27, 33, 45 degrees). These simulations used PROSPECT input parameters Cw, Cp, and Cc assigned nominal values of 0.001 cm, 0.0012 g/cm^2, and 0.002 g/cm^2, respectively, and the scattering parameter N= 1.4 for corn based on their leaf optical measurements. For the SAIL model a spherical leaf angle distribution was chosen. In summary, it was reported that leaf pigment retrieval (Chl a+b) can be achieved through relating the combined optical index TCARI/OSAVI to leaf pigment using simulations with the PROSPECT-SAILH leaf canopy model, as follows:

$$TCARI = 3 * [(R700 - R670) - 0.2 * (R700 - R550) * (R700 / R670)] \quad [1]$$

$$OSAVI = (1 + 0.16) * (R800 - R670) / (R800 + R670 + 0.16) \quad [2]$$

with the prediction relationship:

$$\text{Chl a+b } (\mu g/cm^2) = -30.194 \ln(TCARI/OSAVI) - 18.363 \quad [3]$$

The combined index TCARI/OSAVI achieved high sensitivity to the whole range of leaf total chlorophyll, yet minimizing sensitivity to changes in crop LAI, for the range of solar zenith angle 27 to 45 degrees, and nadir viewing. The evaluation of this algorithm based on field leaf sampling and laboratory pigment analysis in corn at Canadian sites [with Chl a+b ranging from 20 to 52 μg/cm^2 in plots with a large range in nitrogen treatment] and airborne CASI image data [for view/ solar zenith angle ranges (0→17)/(22→35)] showed a correlation between algorithm predictions and field data with r^2 = 0.80 and RMSE = 4.3 μg/cm^2. These algorithms have been subsequently extensively evaluated with CASI hyperspectral data over corn, wheat, and soybean crops at 3 periods during the growing season with similar results.

Accordingly, Equations [1] to [3] were considered to provide a suitable basis for a preliminary assessment of the effects of solar/view geometry changes on the retrieval values of leaf Chl a+b. The DAISEX dataset for Hymap and ROSIS sensors were processed using these algorithms to derive estimates of Chl a+b; results of this analysis and comparison to field data are reported below.

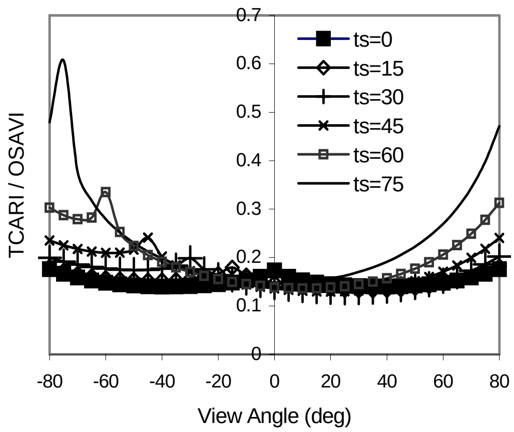
3 APPLICATION TO DAISEX

For the purposes of the inter-comparison and evaluation of biophysical variable retrieval algorithms a database has been generated at the University of Valencia, Spain, to encompass the airborne hyperspectral data processed to above-canopy spectral reflectance (i.e. bi-directional reflectance factor (BRF)), spatially-sampled averages over a 3 pixel x 3 pixel window and the corresponding, nearly-simultaneous field data. The objective of this database was to facilitate ingestion of input files containing all the information needed for variable retrievals, assessment of dependence on sun/view geometry, specific sensor, as well as assessment against field data. See Muller and Hausold (2001) and the DAISEX web site: http://io.uv.es/projects/daisex for details on the flights, sensors, and ground data methods for data collection at Barrax, Spain in 1998, 1999 and 2000.

Prior to proceeding with the analysis approach proposed above, two important questions arise to guide us in the selection of data to be processed, and in the context in which results are to be interpreted. The issues are: (i) pigment content retrieval algorithm sensitivity to spectral position and bandwidth of the sensor systems which have generated the DAISEX data image set (DAIS, Hymap, and ROSIS in this case (Muller et al., 2001)), and (ii) pigment content retrieval algorithm sensitivity to the range in sun-view geometry of the DAISEX data set.

With respect to the first issue we emphasize that the algorithm proposed (Haboudane et al. 2002) is derived using model simulations at 5 nm spectral sampling, and narrow bandwidths. The Chl a+b prediction Equation [3] is premised on measurements at spectral positions 550, 670, 700, and 800 nm. Haboudane *et al.* (2002) describe that additional calculations using nearby wavelengths differing from the nominal by up to 5 nm revealed quick degradation of the LAI-insensitivity performance of the TCARI/OSAVI index. Accordingly, based on the reported FWHM bandwidths in the visible-NIR spectral range of 25 nm, 16 nm, and 7.5 nm for DAIS, HYMAP and ROSIS, respectively, only data from the latter two sensors were considered suitable for this investigation. In fact, although HYMAP data will be subject to some errors that warrant additional investigation for this algorithm its inclusion was considered necessary to provide the range of solar zenith angles and view angles required for this study. In addition, individual HYMAP and ROSIS spectra were re-sampled to the specific wavelengths of the algorithm to allow its correct application.

With respect to the second issue of the pigment retrieval sensitivity to sun/view geometry changes, PROSPECT–SAILH simulations which performed to examine view-solar angle effects on Chl a+b Retrievals for the model parameters (Chl a+b = 40; N=1.5; Cw=0.01; Cm=0.01; hotspot = 0.1; LAI=2; LADF = spherical) for a range of view-sun angles in the solar plane (Figure 1). Results of the sensitivity analysis demonstrate that large variations of TCARI/OSAVI are found at view angles larger than 40°, with very small effects on the index when the view angle is near nadir (Figure 1, top). The effects of the view and sun angle on the estimated Chl a+b through the prediction relationship [Eq. 3] are within the RMSE of accuracy at view angle range of 0-30°, with less than 5 μg/cm^2 error (Figure 1, bottom). These results indicate the robustness of the prediction relationship based on the TCARI/OSAVI index, with small perturbations due to the viewing geometry and therefore suitable for *scaling up* for a different range of sun angle and view angle conditions.



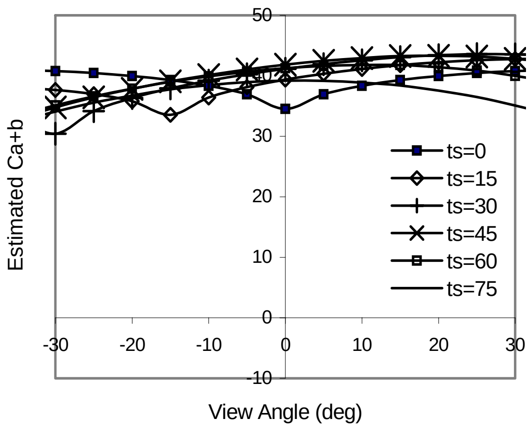


Figure 1. Expected Retrieval Errors for Chl a+b using predictive relationships based on TCARI/OSAVI & *scaling-up* approach Chl a+b > 5 μg/cm^2 RMSE in hotspot and VZA > 20. Thus observable systematic changes in pigment retrieval results are indicated for the range of view-sun angles in DAISEX data, nevertheless, with expected errors < 10 μg/cm^2.

4 ANALYSIS OF DAISEX 1999, 2000 DATA

The results of analysis is first reported as averages and standard deviation on a sampling transect by transect basis. Tables 1 and 2 show results on this basis for 2000 and 1999, respectively. The important comparison is between columns 5 and 6 which represent algorithm-derived and field-measured total chlorophyll content averaged over the number of sampling points in each transect, followed by the standard deviation (SD) for each transect. Details about the field vegetation sampling at Barrax are described in Garcia et al. (2001) and Moreno et al. (2001). In general, field data exhibit a much higher SD than the airborne data for each specific transect. Further, field averages often differ significantly from retrieved pigment averages.

Table 1: Crop Biophysical Field Data and Model Estimated Chl a+b for Selected Crops/Fields: DAISEX-2000. [Barrax Site 2000 data collection: bar1 and bar2 are parallel flight lines, flown perpendicular to the solar plane; dataset “h00bar1” designates Hymap sensor (h), 2000 (00), flight line 1(bar1)]

Crop	Field ID	Sampling Points in transect	Plant Height in m.	% Cover (SD)	Estimated Chl_a+b (SD) in $\mu g/cm^2$	Field Chl_a+b (SD) in $\mu g/cm^2$	Date	Airborne DataSet ID
Alfalfa	V29	1-15	0.5	94.8 (3.1)	26.9 (0.9)	13.0 (3.3)	29-June-00	h00bar1
		1-15	0.5	94.8 (3.1)	33.2 (1.2)	13.0 (3.3)	29-June-00	h00bar2
		1-15	0.5	94.8 (3.1)	41.9 (2.5)	13.0 (3.3)	29-June-00	r00bar2
Corn	V1	1-10	0.9	60.2 (11.7)	39.9 (2.1)	35.9 (8.5)	29-June-00	h00bar1
		1-10	0.9	60.2 (11.7)	46.8 (1.9)	35.9 (8.5)	29-June-00	h00bar2
		1-10	0.9	60.2 (11.7)	49.2 (2.4)	35.9 (8.5)	29-June-00	r00bar1
Corn	V14b	1-5	0.9	83.2 (2.9)	43.5 (1.6)	38.9 (15.4)	29-June-00	h00bar1
		1-5	0.9	83.2 (2.9)	47.3 (0.8)	38.9 (15.4)	29-June-00	h00bar2
		1-5	0.9	83.2 (2.9)	54.4 (1.8)	38.9 (15.4)	29-June-00	r00bar1
S. Beet	V20	1-4	--	67.8 (8.3)	13.8 (0.7)	17.0 (7.6)	29-June-00	h00bar1
		1-4	--	67.8 (8.3)	22.4 (1.1)	17.0 (7.6)	29-June-00	h00bar2

Table 2: Crop Biophysical Field Data and Model Estimated Chl a+b for Selected Crops/Fields: DAISEX-1999. [Barrax Site 1999 data collection: bar1 (north-south) flight line; bar2 (east-west); dataset “h99bar1_12” designates Hymap sensor (h), 1999 (99), bar1 (north-south line), and nominally 12:00 local time (12)]

Crop	Field ID	Sampling Points in transect	Plant Height in m.	% Cover (SD)	Estimated Chl_a+b (SD) in ug/cm^2	Field Chl_a+b (SD) in ug/cm^2	Date	Data Set
Alfalfa	V16	1-6	0.6	--	36.2 (0.6)	26.8 (6.7)	3-June-99	h99bar1_12
		T1-T15	0.6	--	44.8 (1.2)	15.7 (5.8)	4-June-99	h99bar1_15
		M1-M15 MC1-MC8	0.6	--	32.9 (1.3)	27.0 (13.4)	4-June-99	h99bar1_9
		1-6	0.6	--	26.0 (3.9)	26.8 (6.7)	3-June-99	h99bar2_12
		T1-T15	0.6	--	41.4 (1.4)	15.7 (5.8)	4-June-99	h99bar2_15
		M1-M15 MC1-MC8	0.6	--	38.7 (1.6)	27.0 (13.4)	4-June-99	h99bar2_9
Barley	V20	1-12	0.6	68	--	7.2 (2.3)	3-June-99	h99bar1_12
		1-12	0.6	68	--	7.2 (2.3)	3-June-99	h99bar2_12
Corn	SV3	B1-B6 A7-A15 C1-C5	0.2	--	--	54.6 (44.0)	4-June-99	h99bar1_9
		B1-B6 A7-A15 C1-C5	0.2	--	--	54.6 (44.0)	4-June-99	h99bar2_9
S. Beet	SV6	1-7 B6-B15 C16-C20	0.1 0.1	-- --	35.3 (3.3) 42.0 (2.6)	42.2 (18.2) 33.9 (21.8)	3-June-99 4-June-99	h99bar1_12 h99bar1_12
		A1-A5 B6-B16 B16-C20	0.1	--	37.0 (1.8)	24.5 (20.4)	4-June-99	h99bar1_15
		1-7	0.1	--	29.5 (3.4)	42.2 (18.2)	3-June-99	h99bar1_9
		B6-B15 C16-C20	0.1	--	39.4 (2.7)	33.9 (21.8)	4-June-99	h99bar2_12
		A1-A5 B6-B16 B16-C20	0.1	--	38.8 (1.6)	24.5 (20.4)	4-June-99	h99bar2_15

The results of some detailed investigations are shown below in Figures 2 -5. To begin, we illustrate the potential of the DAISEX data set in Figures 2 and 3. In Figure 2 the results for 2000 from Hymap and ROSIS for a single transect for corn, (Field V-1). Although retrievals are similar, systematic differences between the two views (bar 1 versus bar 2) are noted, and can be considered likely a result of view geometry differences.

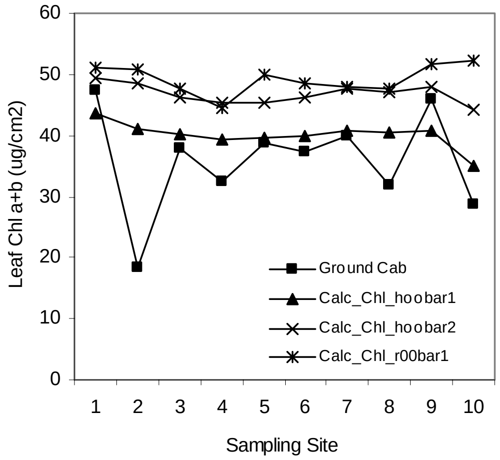


Figure 2. Comparison between field data for corn field V1 and variable retrieval estimates by sensor (Hymap – h; ROSIS – r) and different sensor view (Bar 1 vs Bar 2) for 2000.

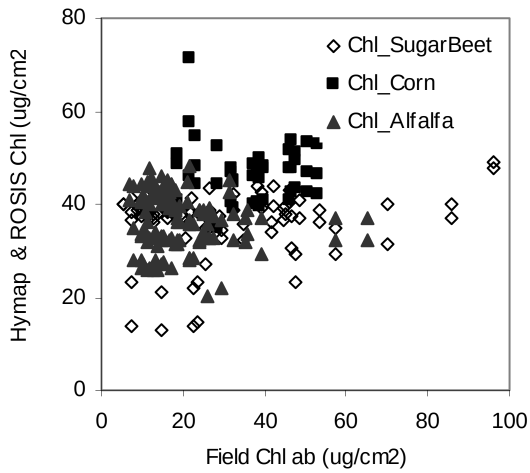


Figure 4. DAISEX 99 and 00 Chl a+b retrieval results from Hymap and ROSIS, for all observations, showing a correlation $R^2 = 0.04$.

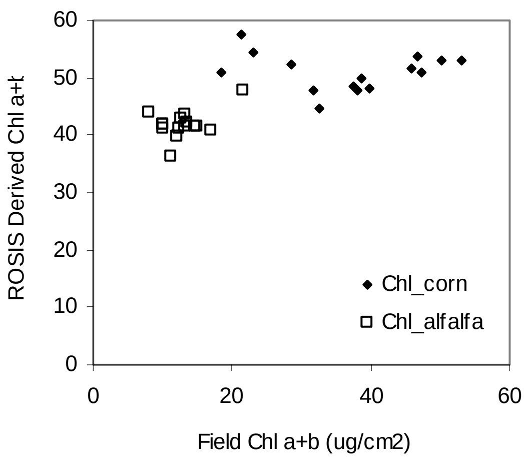


Figure 3. Assessment of ROSIS Chl a+b retrieval results for 2000 for two different crops, alfalfa and corn.

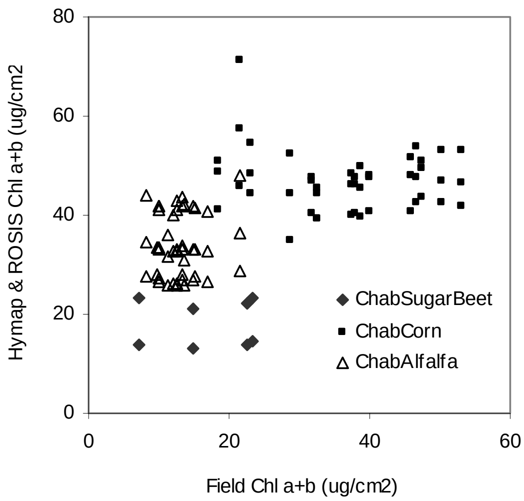


Figure 5. Chl a+b retrieval results for HYMAP and ROSIS using only 2000 data, which shows a correlation improving to $R^2 = 0.30$.

In Figure 3 the retrieved results are compared to field-measured Chl a+b for all relevant ROSIS data. This figure illustrates a general observation from this analysis; the observed range of Chl a+b in the field data was significantly larger than in the retrieved results.

Next we show the global analysis results: that is, the comparison between retrieval results from all Hymap and ROSIS data compared with field data. In Figure 4 we show this comparison for all sampling points for DAISEX 1999 and 2000, whereas in Figure 5 we show only results from the 2000 DAISEX campaign. Clearly, the correlation between retrieved and field Chl a+b data improves from R^2 = 0.04 to R^2 = 0.30 when only 2000 data is used. There are many possible explanations for the results above: model estimate sensitivity to view/solar variations, different spatial scales between field and airborne averaging, data quality in field sampling, etc. Issues related to spatial sampling and variability has received considerable attention within the DAISEX community and questions about the consistency of field data quality has also been raised (personal communication). These issues will require further attention as to their interpretation and significance, beyond the scope of this study at this time.

Nevertheless, if an adequate assessment of algorithm performance in terms of absolute accuracy is not easily obtained from this data set for Chl a+b, it is still possible to address issue of the sensitivity of estimates of crop variables to view/solar direction changes or to different sensors for identical sampling lines. This is the objective of the subsequent analysis.

The retrieved results are compared for pairs of flights, bar 1 and bar 2, each pair occurring with minimal change in solar zenith angle (SZA) between them but with differences in view zenith angle (VZA) for any specific field sampling site observed. All sampling sites and crops for which a pair of airborne measurements were available were used in this analysis. A summary of the results of this study of sensitivity of the retrieval results on the view-sun geometry is depicted in Figure 6, in which Chl a+b estimated from one sun-view geometry configuration are plotted against those from another sun-view geometry. For 1999 different sun-view geometries can be compared for image acquisition nominally at times 9:00, 12:00 and 15:00 whereas for 2000 only one sun-view geometry condition was available.

Some systematic dependencies on sun-view geometry are seen in Figure 6. In general such differences appear to be less that 10 μg/cm^2, in agreement with the model simulations on expected sensitivity (Figure 1). However, the 1999 Barrax data acquired near 12:00 show much higher discrepancies suggesting the need for a canopy model which properly accounts for sunlit soil contributions.

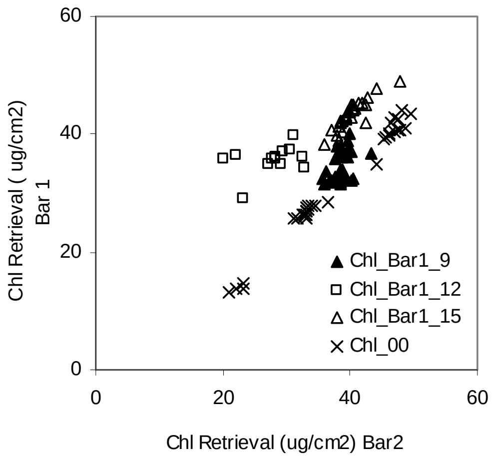


Figure 6. Retrieval sensitivity to view-sun geometry effects – all crops 1999 & 2000: same sites, different views.

5 CONCLUSIONS

Optimized index and scaling up with PROSPECT-SAILH with parameters appropriate to a particular sun-view geometry was previously seen to provide an approach to mapping canopy Chl a+b with RMSEs < 5 μg/cm^2 using a Canadian data set (Haboudane et al. 2002). For DAISEX '99 and '00 data from Hymap & ROSIS differences between field data and retrievals far exceeded expected errors. However, sun-view angle differences in retrievals observed in DAISEX data provide the basis for further analysis into the angle-sensitivity of retrieval approaches on a relative basis only (due to unexplained discrepancies with field data).

These results suggest some systematic effects exist which need study and explanation: differences between ROSIS and Hymap when sampling the same transect, or differences between Hymap estimates as a function of view/azimuth angles. In this study the magnitude of these systematic differences and the specific pairs of flights showing largest anomalies have been identified.

One disadvantage of the scaling-up approach used in this preliminary analysis is the dependence of the prediction algorithm on the specific wavelengths or on bandwidth used in the modeling. Therefore a more generic inversion methodology is deemed to offer the flexibility needed to continue this study.

6 REFERENCES

Blackburn, G. A. (1999), Relationships between spectral reflectance and pigment concentrations in stacks of deciduous broadleaves. Remote *Sens. Environ.* 70: 224-237.

Datt, B. (1999), A new reflectance index for remote sensing of chlorophyll content in higher plants: tests using Eucalyptus leaves. *J. Plant Physiol.* 154: 30-36.

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

Demarez, V., and Gastellu-Etchegorry, J. P. (2000), A modeling approach for studying forest chlorophyll content. *Remote Sens. Environ.* 1: 226-238.

Garcia, J. C., C. Cinat, F. Montero, A. Brasa, L. Alonso, M. C. Gonzalez, J. R. Ruiz, C. Martinez, A. Palacios, and J. Moreno (2001), Vegetation and soil measurements at Barrax. *Proc. DAISEX Final Results Workshop,* ESA SP-499, pp.79-87, held ESTEC, Netherlands 15-16 March 2001.

Gitelson, A. A., Merzyak, M. N., and Lichtenthaler, H. K. (1996), Detection of red edge position and chlorophyll content by reflectance measurements near 700 nm. *J. Plant Physiol.* 148: 501-508.

Haboudane, D., Miller, J. R., Tremblay, N., Zarco-Tejada, P. J., and Dextraze, L. (2002). Integrated narrow-band vegetation indices for prediction of crop chlorophyll content for application to precision agriculture, *Remote Sens. Environ.* 81:416-426.

Jacquemoud, S., and Baret, F. (1990), Prospect: A model for leaf optical properties spectra. *Remote Sens. Environ.* 34: 75-91.

Kuusk, A. (1985), The hot spot effect on a uniform vegetative cover. *Sov. J. Remote Sens.* 3: 645-658.

Moreno, J., L. Alonso, M. C. Gonzalez, J. C. Garcia, C. Cunat, F. Montero, A. Brasa, O. Botella, R. J. Zomer, and S. L. Ustin (2001), Vegetation properties from imaging data acquired at Barrax in 1998, 1999 and 2000. *Proc. DAISEX Final Results Workshop*, ESA SP-499, pp.197-207, held at ESTEC, Netherlands 15-16 March 2001.

Muller, A. and. Hausold, A. (2001), The airborne imaging spectrometer data acquisition programme in 1998, 1999 and 2000. *Proc. DAISEX Final Results Workshop,* ESA SP-499, pp. 7-11, held at ESTEC, Netherlands 15-16 March 2001.

Muller, A., Gege, P., and Cocks, T. (2001), The airborne imaging spectrometers used in DAISEX. *Proc. DAISEX Final Results Workshop,* ESA SP-499, pp. 3-6, held at ESTEC, Netherlands 15-16 March 2001.

Verhoef, W. (1984), Light scattering by leaf layers with application to canopy reflectance modeling: The SAIL model. *Remote Sens. Environ.* 16: 125-141.

Zarco-Tejada, P. J., Miller, J. R., Noland, T. L., Mohammed, G. H., and Sampson, P. H. (2001), Scaling-up and model inversion methods with narrow-band optical indices for chlorophyll content estimation in closed forest canopies with hyperspectral data. *IEEE Trans. on Geoscience and Remote Sens.* 39: 1491-1507.