

The DAISEX Campaigns in Support of a Future Land-Surface-Processes Mission

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Introduction

Part of ESA's Earth Observation Envelope Programme (EOEP) is intended to advance our understanding of the various processes occurring in the Earth's biosphere/geosphere, and their interactions with the atmosphere. Thus, the Programme's 'Theme 3: Geosphere/Biosphere' focusses on the modelling and monitoring of land-surface processes, the study of interactions, and the analysis of climate impacts on the biosphere, with the objective of enhancing our skills in predicting the evolution of the Earth system.

Real-life applications such as weather forecasting, crop-yield estimation, precision farming, the management of renewable and non-renewable resources, as well as environmental-hazard monitoring/forecasting, would all benefit from improved process model descriptions.

A spaceborne scientific mission addressing the provision of information on geospheric/biospheric processes and their interactions with the atmosphere is currently being formulated. This mission implies the need for an instrument with high spectral and angular resolution and a very high radiometric performance, operating in the reflective and thermal parts of the spectrum, not only to identify but also to quantify the key variables driving the processes.

Background

The Earth's environment is a complex system that couples, on various temporal and spatial scales, the atmosphere, the oceans, the land and the cryosphere. Many aspects of the functioning of the Earth system are still not fully understood. In order to enhance still further our capacity to predict the evolution of the Earth's environment under the influence of both natural variability and human activities, the provision of

In the last ten years, the retrieval of geo-/biophysical parameters from airborne imaging-spectrometer data has made significant progress. ESA therefore decided to investigate the feasibility of quantitatively retrieving geo-/biophysical variables as the requisite inputs for process models. For three years in succession (1998 to 2000), therefore, the Agency has conducted an airborne imaging-spectrometer campaign called 'The Digital Airborne Imaging Spectrometer Experiment (DAISEX)' in support of a possible future spaceborne mission. The instruments flown included DAIS 7915, HYMAP, ROSIS, POLDER and LEANDRE.

This article describes the state of the art in retrieving variables relevant to land-surface processes from hyperspectral data cubes, outlines the scientific objectives, and demonstrates the first results of the DAISEX campaigns.

data and their integration into appropriate models is of paramount importance. To better understand and predict processes occurring in the different ecosystems, estimates of 'process-driving' variables are needed. The capability to observe the Earth with a range of instruments providing different spatial, radiometric, temporal and angular resolutions is expected to result in major advances in process monitoring and management. Such considerations underlie the formulation of ESA's Earth Observation Envelope Programme.

For this Programme, two classes of Earth Observation missions have been identified for the post-2000 time frame: the *Earth Watch* and the *Earth Explorer* missions. Earth Watch missions are pre-operational missions concerned with operational needs requiring continuous data provision. Earth Explorer missions are focussed on research and demonstration. They are further subdivided into Earth Explorer Core Missions, which are larger missions led by ESA, and Earth Explorer Opportunity Missions, which are smaller and more flexible missions, not necessarily led by ESA.

One of the first set of Earth Explorer Core Missions, which were the subject of Phase-A studies, was the Land-Surface Processes and Interaction Mission (LSPIM). This mission's core instrument was a hyper-spectral imager covering the visible, near-infrared, shortwave-infrared and thermal-infrared spectral ranges.

Following the User Consultation Meeting in Granada (Spain) in October 1999, LSPIM was not selected, but was assessed as being of

high scientific merit. SPECTRA – a mission with similar but more focussed and refined objectives – was proposed to the Agency in response to the Call for Ideas for the next Earth Explorer Core Missions. Its scientific objectives and technical and programmatic feasibility are currently under evaluation.

Within the framework of the Earth Observation Preparatory Programme (EOPP), ESA carries out various airborne campaigns to support the development of geo-/biophysical retrieval algorithms, calibration and validation and simulation for future spaceborne Earth Observation missions. It was within this framework that the DAISEX campaigns were organised in 1998, 1999 and 2000, involving test sites in Spain, France and Germany and exploiting a range of airborne instruments. The overflights were accompanied by an intensive field-measurement programme.

DAISEX is intended to provide airborne hyperspectral measurements over land, to demonstrate the retrieval of variables as required for future land-surface-process missions.

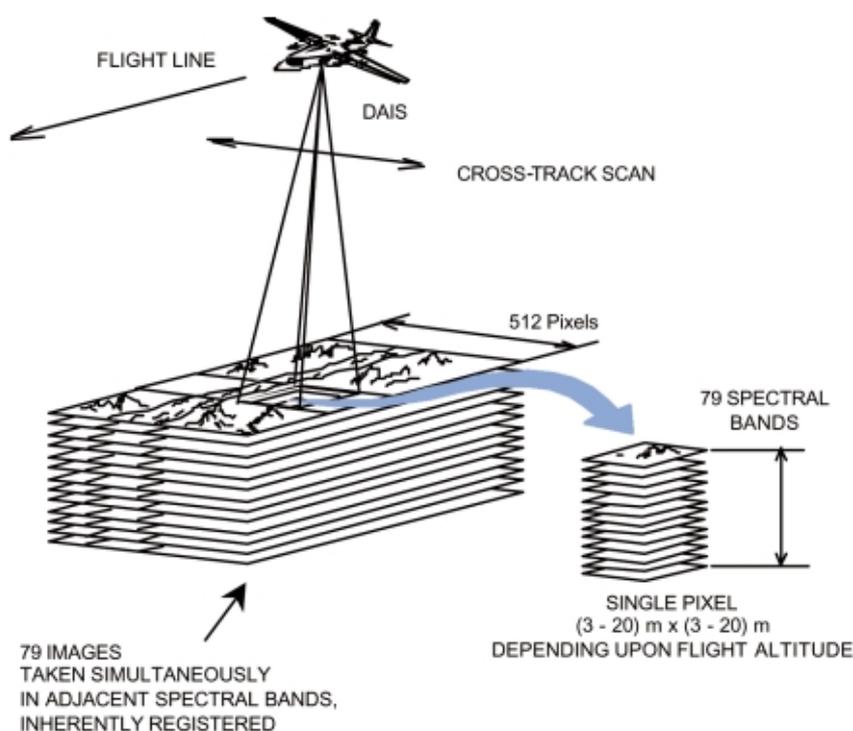
Information gathering

Passive optical sensors operate in the reflective and thermal parts of the electromagnetic spectrum. The sources of information they observe are the radiance fields emitted or reflected from the Earth's surface. On its path through the atmosphere, the irradiance interacts with the atmospheric particles and gases before reaching the sensor. Assuming that all interactions caused by the atmosphere can be accounted for, information on the surface should be retrievable. These 'disturbing interactions' caused by the atmospheric constituents (gaseous molecules and aerosols) contain information useful for atmospheric research.

The chemical and physical condition of the surface defines the intrinsic information in the reflected or emitted radiance field. Its retrievability depends on the spatial, spectral, angular and radiometric resolution of the observing instrument.

The basic concept of an imaging spectrometer is shown in Figure 1. The sensor scans the top-of-the-atmosphere radiance within its instantaneous field of view (IFOV). The flight altitude and the IFOV define the footprint size of each pixel, often referred to as the ground instantaneous field of view (GIFOV). The incoming radiance is dispersed into its spectral components by a spectrometer. As the instrument moves forward it records line-by-line, building up an image data cube.

Figure 1. Illustration of hyperspectral data cube acquisition



As already mentioned, the chemical and physical condition of the surface defines the information intrinsic in hyperspectral data cubes. Generally, the reflectance (ρ) can be described as a function of the wavelength (λ), the location (\vec{r}), the time of observation (t), the viewing direction (ϑ) and the polarisation (p), such that

$$\rho = f(\lambda, \vec{r}, t, \vartheta, p)$$

Polarisation plays an important role for atmospheric scattering, but is of minor influence for natural surfaces and thus can be neglected.

The viewing direction and the directional anisotropy behaviour of different surfaces were only marginally addressed in the early days of remote sensing due to lack of data, but are currently the subject of much on-going research. Sensors like MISR and POLDER foster these research topics by providing multi-angular and multi-spectral data sets.

Anisotropic reflectance is caused by multiple scattering within the surface (e.g. canopy) and is thus a function of the structure of the interacting media. It may contain meaningful information about, for example, the number and size of the leaves (Leaf Area Index – LAI), their orientation (Leaf Inclination Distribution Function – LIDF), and the height of the canopy. It may therefore be able to provide indicators of the condition of the vegetation. A prominent feature of the directional anisotropy effect is called the ‘hot spot’, which is the increased reflectance when the surface is viewed in the same direction as it is illuminated by the Sun (same line of sight). Recent research showed that the half-width of the hot spot contains useful information about the condition of the vegetation. Usually, there is a parameter ‘q’ associated with the hot spot, defined as its width/height ratio. In order to get a good estimate of q, one of the aims is to observe from as many different viewing directions as close to the hot spot as possible.

Anisotropic effects can be assessed via the experimental Bidirectional Reflectance Factor (BRF), which is the ratio of the directionally reflected radiance from the surface target and the nadir radiance of a Lambertian-scattering reference target. The Bidirectional Reflectance Distribution Function (BRDF) describes the angular behaviour of the surfaces, and it can be assessed by measuring the BRF.

Compared with the limited angular range of airborne and spaceborne data sets, experimental directional reflectance factors (acquired with field goniometers) are quite plentiful and enable us to determine the BRDFs of the objects for quite a number of viewing and illumination geometries.

Figures 2 and 3 show two examples of experimental directional reflectance factors, namely those for bare soil and for alfalfa acquired during DAISEX ‘99 with the Swiss field goniometer. Note that the highest reflectance, which forms the peak of the hot spot, cannot be measured with the field goniometer due to the shading of the target by the instrument.

Diurnal directional measurements show the variability of the reflectance factors due to changing illumination geometry, i.e. changing solar zenith angle.

The spectral effects of the anisotropy can be analysed by normalising the BRF with a

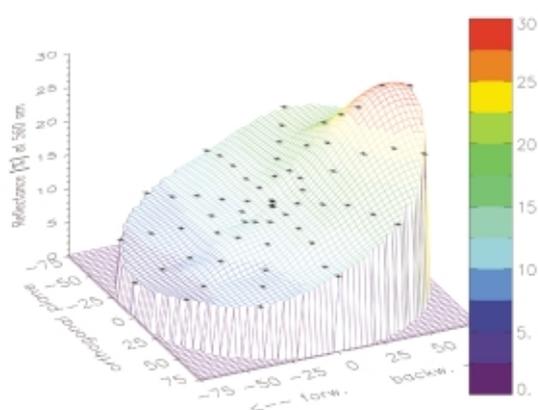


Figure 2. Bidirectional Reflectance Factors (BRFs) of bare soil for 65 different viewing angles at 560 nm (Sun azimuth 94° and zenith angle 49°; symbols indicate measured data points)

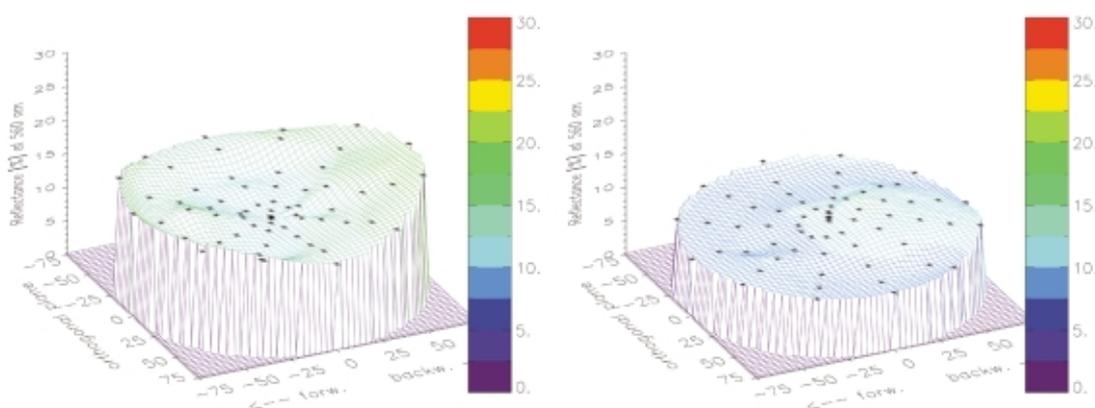


Figure 3. Bidirectional Reflectance Factors of a dense alfalfa canopy for two different illumination angles at 560 nm (left: Sun azimuth 90°, zenith 53°; right: Sun azimuth 182°, zenith 17°)

Figure 4. Comparison of alfalfa nadir reflectances ratioed with the spectral albedo for six different solar zenith angles

representative spectrum of the object (e.g. a nadir-view spectral signature or the spectral hemispherical albedo derived from the BRF measurements). Figure 4 shows an example of the spectral dependence of anisotropic effects for the measured alfalfa canopy with different solar zenith angles.

One of the objectives of DAISEX was to assess the use of multi-angular-hyperspectral data to enhance the retrieval of structural biophysical variables such as the LAI.

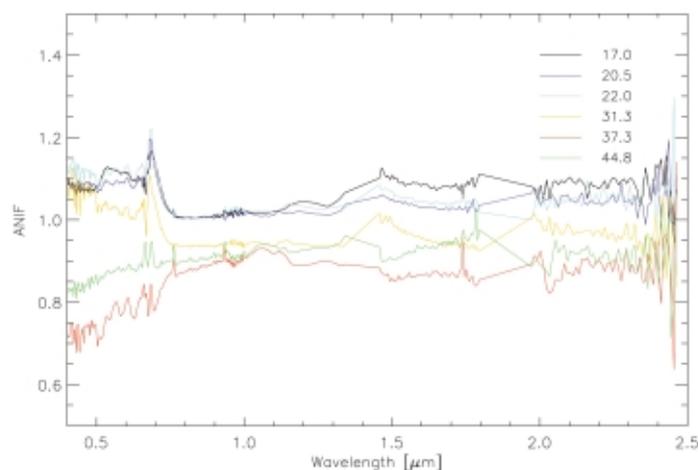
Information retrieval

Basically, three different types of retrievals can be distinguished:

1. Classical retrievals

Classical retrievals use system, atmospherically and geometrically corrected data sets as input data. Each pixel represents the reflectance on the ground within the footprint of the sensor. Different correction schemes are used to atmospherically correct the data. Semi-empirical methods are mainly used to correct for atmospheric scattering effects. These techniques are considered sufficient for broadband sensors, which are affected to only a minor extent by atmospheric gaseous absorption features. More sophisticated techniques are required for the narrow-band hyperspectral data sets. For these data, atmospheric radiative transfer models, constrained by radiosonde measurements or the use of standard atmospheric profiles, are used. High calibration accuracy is a prerequisite. Calibrations are performed to convert the recorded digital counts into radiance values. The latest developments in the atmospheric-correction schemes consider the different viewing directions within one scanning line, as well as the topography of the terrain. On-going research focusses on the inclusion of the anisotropic reflectance effects of different surface types.

The derived reflectance values are used to produce higher-level products (Level-2), which may in turn be used to derive further products (Level-3), for instance estimating LAI from vegetation indices. The latter were derived by relating the increased reflectance values of vegetation in the near-infrared to the reflectance of vegetation in the visible red (red edge), and using an established empirical relationship between the indices and LAI. Another technique fits the red edge to a Gaussian function, the coefficients of which are then related to vegetation variables in a semi-empirical way.



Currently, the most commonly used techniques for quantitatively retrieving variables from hyperspectral data are un-mixing and differential absorption techniques. The latter use the fact that the depth of the absorption is correlated with the weight percentage of the material observed. Thus, absorption depths in specific spectral bands can be used to quantify the amount of the material present. For this technique, the absorption feature needs to be fully observed, including both of the inflection points left and right of the absorption feature. Un-mixing techniques assume that the observed spectrum within the footprint of the sensor is a combination of the spectra of all pure spectral end-members (spectrally 'pure' material) within this footprint. Even though the combination is unlikely to be linear, it has been proved that the assumption of a linear combination (as often applied) gives reasonably good results. End-members can be selected from the data set itself by identifying 'pure' pixels within the scene, or using spectral libraries.

It should be noted here that spectral libraries are also being used to train 'classifiers', e.g. neural networks. In this case it is the image that is classified rather than variables quantitatively retrieved. Another technique that falls into this category is the Spectral Angle Mapper (SAM). This method determines the similarity of each pixel in the image to known library spectra by computing their angle within the spectral space, where the number of spectral bands defines the dimension of the latter.

2. Inversion of coupled radiative transfer models

Intensive research is currently in progress in this area and major advances have been achieved during the past few years. Instead of using a radiative transfer model only for the atmospheric correction, radiative transfer models are developed to describe the optical properties of vegetation and soils. These

models are coupled with the atmospheric transfer models, resulting in complete radiative transfer codes describing the interactions over the entire path of the radiation from the emitted solar irradiance to the Top of the Atmosphere (TOA) radiance recorded by satellite sensors. Variables can then be retrieved by model inversion constrained by ancillary data (e.g. atmospheric profiles measured by a radiosonde, *in-situ* measured micro-climatic data, a-priori knowledge of some of the canopy and soil variables, e.g. gathered by campaign activities). Moreover, comparison of the modelled TOA radiances constrained by ancillary data with the observed TOA radiances makes it possible to analyse and further improve the models.

TOA radiances are used as inputs in the inversion process. Different approaches are proposed for the inversion, such as look-up tables, neural networks, golden-section 3D and Gauss-Newton techniques.

It should be noted that the models also consider illumination- and viewing-angle-dependent effects. This means that the inversion process is further constrained by feeding in additional angular observations. This in turn reduces the number of degrees of freedom available during the inversion, and may enhance the accuracy of the retrieved variables. The latter will then be used as inputs to surface-process models to derive variables of interest to researchers, such as canopy state, fluxes, crop production, etc. These models can be used both for monitoring and forecasting the state of the ecosystem.

3. Assimilation of remote-sensing data into radiative transfer and canopy or soil functioning coupled models

A further development of the technique discussed above is the coupling of the complete radiative transfer models with the surface-process models themselves (canopy and soil functioning models) and assimilating the remote-sensing observations from different sources (optical and SAR data with different spectral and spatial resolutions) in a multi-temporal manner.

Assimilation involves tuning (by means of a cost function) some of parameters of the coupled models so that the simulation matches the observations as closely as possible. This facilitates optimum exploitation of the complementary features of the different sensors. This technique is potentially the most promising because it makes best use of available information, both on the physical or biological processes and any ancillary data.

This technique follows a new philosophy. Instead of retrieving variables directly, it rather aims at stabilising the coupled process models by adjusting variables within the models, making use of assimilation techniques. The stabilised models make it possible to predict the future state of the ecosystem more accurately. The frequent feeding of the models with remote-sensing data accounts for unforeseen events such as hailstorms or other natural hazards, thereby ensuring that the model remains 'on-track'.

This, of course, is a rather ambitious and challenging idea and many scientific questions still remain unanswered. These include the refinements to be introduced into the models, the non-linearity of model scales and the related optimum spatial resolutions, the optimum temporal coverage of the different sensors, the optimum spectral resolution, the optimum number of viewing directions and the required spectral resolution of angular observations, the optimum SAR (band, polarisations and incident angle), etc. Some of these questions were already addressed within the framework of the LSPIM Phase-A.

ESA plans to investigate these questions further through dedicated study activities. The DAISEX campaigns provided suitable data to start addressing some of these questions. A future land-surface-processes mission will certainly help in refining these ideas. Programmes like APEX and CHRIS/PROBA will be useful assets.

The DAISEX campaigns

The main scientific objective of the DAISEX campaigns was to demonstrate the feasibility of quantitatively retrieving geo-/biophysical variables by accounting for atmospheric effects, whilst at the same time analysing the data for possible additional information on directional anisotropy. Bio-/geophysical variables included the leaf area index, biomass, leaf water content, canopy height, chlorophyll content, surface temperatures and emissivity. Since accurate calibration and atmospheric corrections are essential to quantitatively retrieve these variables, *in-situ* atmospheric measurements (needed to derive the atmospheric corrections) were performed in addition to the field measurements for validating calibration and retrieval. The atmospheric modelling for airborne hyper-spectral sensors was carried out based on the ATCOR model. Three airborne campaigns were organised over test sites in Spain, France and Germany, in 1998, 1999 and 2000, exploiting a range of different airborne instruments.

DAISEX Test Sites and Teams

The Barrax Site

The Barrax test site is a well-described agricultural site close to the town of Albacete in Spain. It was formerly used in such international programmes as EFEDA, RESRAPs, RESMEDES, RESYSMED, RISMOP and STAAARTE, which included the exploitation of a range of airborne instruments, e.g. AVIRIS, DAEDALUS, TMS, and AIRSAR. Data from SIR-C/X-SAR as well as operational sensors such as ERS-SAR, Landsat-TM, SPOT-HRV, NOAA-AVHRR, and Meteosat are available. Detailed thematic maps and long-term data records exist. In addition, there are two permanent meteorological stations in the area continuously recording the energy and water fluxes. The School of Agronomical Engineering of the University of Castilla-LaMancha permanently monitors the fields. An additional advantage of the Barrax site is its topography and geomorphology. It is relatively flat, which eases the pre-processing required to correct for geometric and radiometric distortions (needed for the analysis of multi-angular observations).

The Colmar and Harheim Sites

The Colmar site is an agricultural one operated by the Institute National de Recherches Agronomiques (INRA), located south of the city of Colmar in France. The Harheim site is about 20 km southwest of Freiburg in Germany, and is directly adjacent to the Colmar site. During DAISEX, both sites were referred to collectively as the DAISEX 'Upper Rhine Super Site (URSS)'. The URSS is located in the southern part of the Upper Rhine Valley, extending from Karlsruhe to Basel, and from the Vosges to the Black Forest.

The area is a highly uniform flood plain, lying about 200 m above sea level. Much information has been collected on the atmosphere, soil, hydrology, radiation, land occupation and use, and air quality over the years. Remote sensing has been used over the last 15 years (Landsat-TM, SPOT-HRV, NOAA-AVHRR, Meteosat, ERS-SAR). It has been an important area for both national and international research programmes, such as the Regio Klima Project (REKLIP).

The Colmar site includes experimental test fields producing a variety of crops, and experimental vineyards. The site is well-characterised in terms of the physical and chemical properties of its soil and its hydrology, and it includes meteorological stations.

Harheim is a coniferous forest site (*pinus sylvestris*, about 40 years old) run by the Meteorological Institute of the University of Freiburg. It is about 10 km in extent north-south, and about 1.5 km east-west. Intensive measurements have been conducted since 1970, including tree-characterisation (height, density, etc.) and flux measurements. Two towers (30 m and 15 m high) within the site are instrumented with radiometers, ultrasonic anemometer thermometers and fast hygrometers, enabling mass- and energy-flux estimates to be derived. Harheim has been used for both national and international research programmes such as REKLIP.

Teams Involved in the Campaigns

ESA Earth Sciences Division:

Campaign Unit (APP-FSS): Overall management

Land Unit (APP-FSL): Scientific support

DLR, Oberpfaffenhofen:

Flight operation of DAIS 7915, HYMAP and ROSIS. Pre-flight and in-flight calibration of airborne instruments. Radiometric, geometric and atmospheric corrections of DAIS 7915, HYMAP and ROSIS data.

University of Valencia:

Management of ground measurement programme in Barrax, Spain. Data analysis, including data-quality assessment and algorithm validation.

University of Strasbourg:

Management of ground measurement programme in Colmar and Harheim. Data analysis including quality assessment and algorithm validation.

University of Zurich:

Goniometer measurements in Barrax and Colmar. Analysis of goniometer measurements.

CESBIO:

Flight operation of POLDER. Radiometric, geometric and atmospheric correction of POLDER data.

Airborne sensors, flight patterns and acquired data sets

The core instruments used in the DAISEX campaigns were the Digital Airborne Imaging Spectrometer (DAIS 7915), the High-Resolution Imaging Spectrometer (HYMAP), the Reflective Optics System Imaging Spectrometer (ROSIS), and the Polarisation and Directionality of the Earth's Reflectance (POLDER) airborne instrument.

DAIS 7915 is a 79-channel imaging spectrometer operating in the 0.5 to 12.5 μm wavelength range with four grating spectrometers. With the exception of the 1.05 – 1.4 μm region, all atmospheric windows are covered, which is a unique feature of this system. The instrument, purchased from GER Corporation (USA) jointly by the EC Joint Research Centre (JRC) and DLR, has already been flown in Europe since 1995 for a number of different research and commercial projects.

HYMAP is an Australian instrument, built by Integrated Spectronics Pty. Ltd. The sensor provides 126 bands across the reflective solar wavelength region (0.45–2.5 μm) with contiguous spectral coverage (except in the atmospheric water-vapour bands) and bandwidths of 15 – 20 nm. The system operates on a three-axis-stabilised platform to minimise image distortion due to aircraft motion. It provides a high signal-to-noise ratio (>500:1) and thus an industry-standard-setting image quality. Laboratory calibration and operational system monitoring ensure the radiometric performance required for demanding spectral mapping tasks.

ROSIS is a compact airborne imaging spectrometer developed jointly by German industry and research organisations. It provides 115 spectral bands in the spectral range 430 – 860 nm, with 4 nm spectral sampling. It was recently redesigned to provide greater radiometric and spectral stability.

POLDER is a wide field of view radiometer equipped with a 2D CCD array and a filter wheel providing eight spectral bands from 443 to 865 nm. The airborne version has a similar concept to the spaceborne version, but a different spectral band configuration. A given pixel on the ground is projected to different locations on the 2D CCD array, and therefore has different view-angles in successive images. With a specific flight pattern such as that operated by ARAT during DAISEX '99, up to 50 view directions are acquired per pixel. After pre-processing, the BRDF of every pixel is reconstructed up to a 60° viewing angle at 20 m spatial resolution of an area of typically 3 km x 3 km.

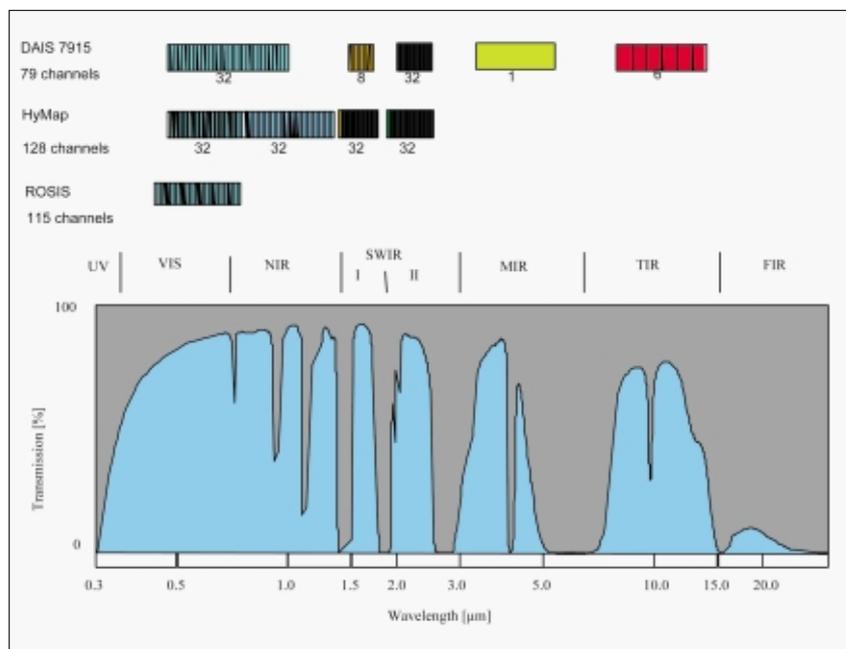


Figure 5. Atmospheric transmission and spectral layout of DAIS 7915, HYMAP and ROSIS

The complementary nature of the various instruments is illustrated in Figure 5, which shows their different spectral layouts in the context of atmospheric transmission.

Data have been acquired under different observation geometries by using crossing flight paths, as illustrated in Figure 6. In particular, the 1999 campaign focussed on the acquisition of multi-angular data, by using three pairs of crossing flight paths – one in the morning, one at midday, and one in the afternoon – over the Barrax site for HYMAP and DAIS 7915. This provided a total of six different view-illumination angles for each pixel in the overlapping area of the flight paths. Observation of the hot spot was assured by the east-west flight line at noon. Table 1 summarises the data acquired by each sensor during the three campaigns.

Figure 6. Flight pattern used during DAISEX '98 over the Barrax test site

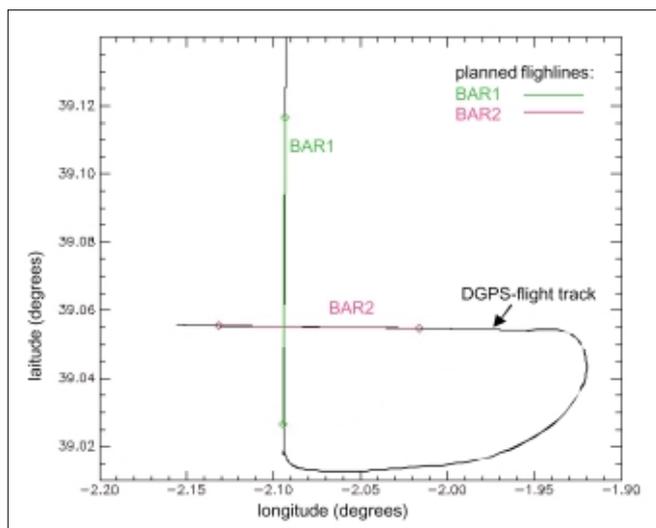


Table 1. Airborne data acquired during DAISEX campaigns

	Barrax, Spain				Colmar, France				Hartheim, Germany			
	D	H	P	R	D	H	P	R	D	H	P	R
DAIS 7915												
HYMAP												
POLDER												
ROSIS												

The most complete data set was acquired over the Spanish test site. Thanks to an EC-funded project, the French ARAT aircraft, equipped with the LEANDRE atmospheric-measurement instrument, could be operated simultaneously with DAIS and HYMAP over the Spanish site in 1999. This allowed the acquisition of a complimentary data set, something that had never been done before. The combination of HYMAP (VNIR, SWIR component), DAIS (VNIR, SWIR, TIR component) and POLDER (angular component) data enabled us to simulate the instrument as it was proposed by LSPIM. The ARAT instrument provided a 3D characterisation of the atmosphere at the time of the overflight.

Ground measurements

The field measurements involved a suite of instruments operated by the various research teams. The direct and diffuse solar irradiation was measured with high spectral resolution (6 nm) for atmospheric characterisation. In-situ aerosol characterisation was also performed by a particle counter and nephelometer on ARAT, enabling us to estimate aerosol extinction profiles. Ground-based reflectance measurements were mainly acquired for two reasons: (a) those of relatively homogeneous targets for system-calibration purposes, and (b) those to radiometrically characterise principal soils and vegetation. The latter were also performed under different viewing geometries exploiting a field goniometer. Figure 7 shows the Swiss

goniometer for BRDF measurements as operated during the DAISEX '99 campaign. All field measurements were geo-referenced using GPS for later integration of the data into Geographical Information Systems (GIS).

Detailed mapping included crop identification, phenological state description and soil-roughness measurements. Soil and crop samples were collected for later laboratory analysis of the soil's mineral composition and the biochemical contents. Validation measurements included LAI, fPAR, chlorophyll content, surface temperature, surface emissivity and evapotranspiration.

At the URSS* particular attention was paid to measurement of the radiative-balance, energy-flux and directional TIR-radiance components for modelling and evaluating the surface energy balance. In-situ radiosonde measurements were made to obtain temperature, ozone, pressure and humidity profiles up to an altitude of 30 km. These measurements are used to constrain the atmospheric transfer codes used for atmospheric corrections. Radio sounding was supported by the Spanish National Institute of Meteorology and Meteo France.

Preliminary results

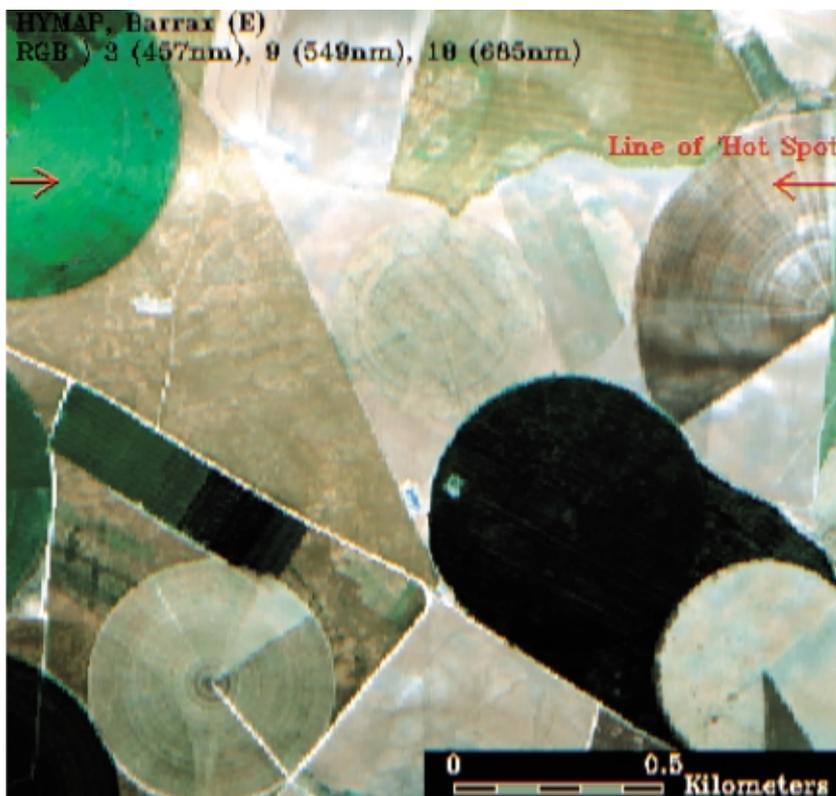
Pre-processing of DAIS 7915, HYMAP and ROSIS data included radiometric, geometric and atmospheric corrections, carried out by

* URSS = the DAISEX Upper Rhine Super Site



Figure 7. The Swiss goniometer at the Barrax site

DLR. First results are presented in Figure 8, where HYMAP data with a spatial resolution of about 6 m x 6 m, acquired over Barrax during DAISEX '99, are shown. The image is a 'true-colour' composite using bands 18,9,3 (0.685, 0.549, 0.457 μm) for red, green and blue, respectively. For visualisation purposes, the image was enhanced using standard image-processing tools. Irrigated field patterns of different sizes (circled objects) are shown. Different shades of green indicate different types and growing stages of vegetation and crops. Brownish to greyish colours show fields with sparse vegetation and bare soil; gravel roads appear as white lineaments.



Data acquired during the DAISEX '99 campaign show the 'hot spot' in hyper-spectral data cubes for the first time; it appears as a bright horizontal line in the upper part of the image.

POLDER images of the 3 km x 3 km Barrax area at 865 nm for three positions of the plane (along the same flight line, within a time interval of a few seconds) are presented in Figure 9.

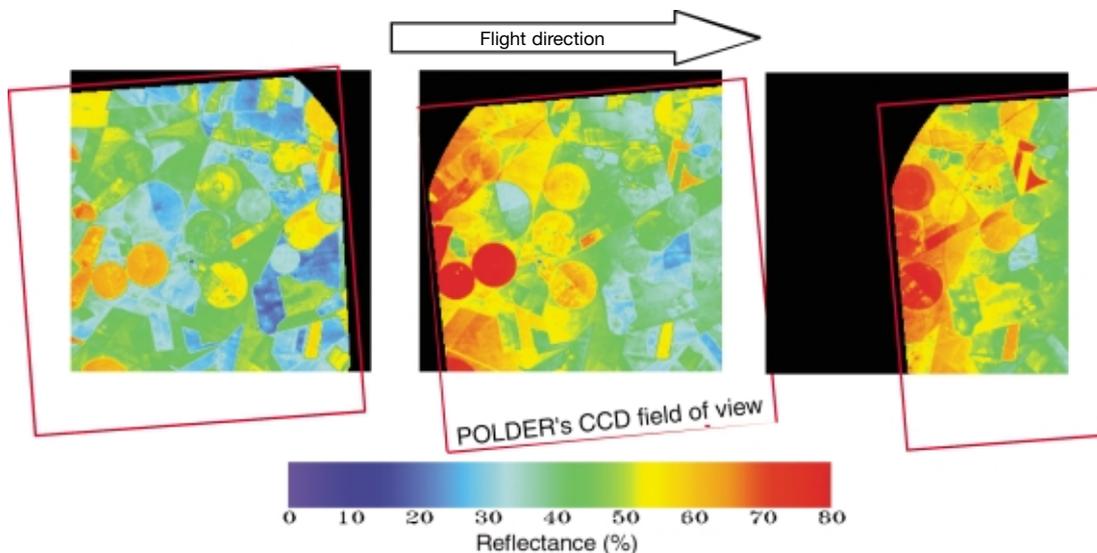


Figure 8. HYMAP data acquired over Barrax

Figure 9. POLDER images of the 3 km x 3 km Barrax area at 865 nm for three positions of the viewing plane (courtesy of Luis Alonso, Univ. of Valencia)

The different aspects of the three images are due to the different view-target-Sun configurations (the Sun is located to the bottom-right of the images). The image sequence shows the hot spot, characterised by a sharp increase in surface directional reflectance when illumination and viewing geometry are in coincidence. The processing of all images acquired during the flight permits the full BRDF of every 20 m pixel of the area to be reconstructed.

Figure 10 shows the reflectance at 2200 nm (SWIR-II) extracted from the HYMAP image for different viewing zenith angles. Several fields with the same vegetation coverage were used for this purpose. The hot spot is clearly visible at a view zenith angle of 16.8°, also in the

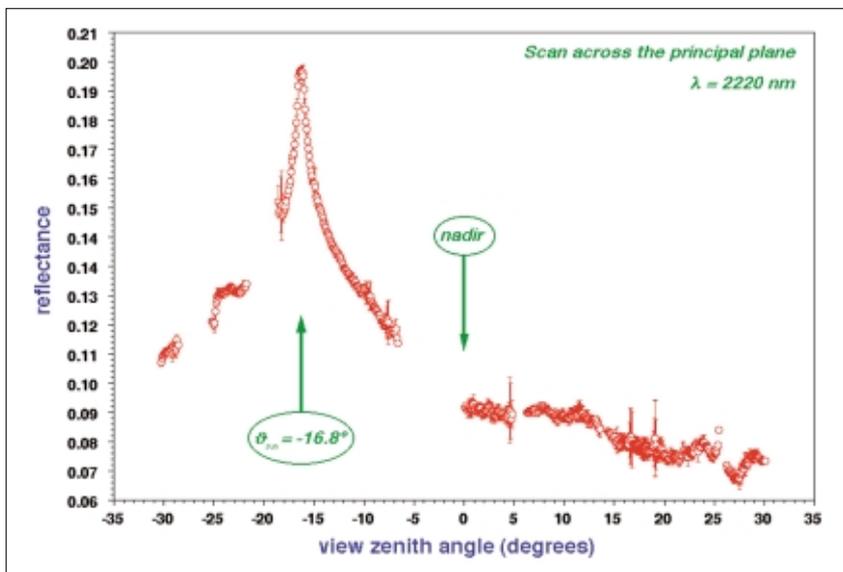


Figure 10. Reflectance of alfalfa at 2200 nm for different view zenith angles extracted from HYMAP data



Figure 11 a,b. BRDF correction with a class-specific Ambrals Model fit

SWIR-II, which proves the good radiometric performance of the HYMAP sensor. Note that the image was acquired on 4 April, when the Sun was close to latitude 20°N, which with the observed hot spot at 16.8° adds up to about 37°, which is the latitude of the test site.

Figure 11a shows a cross-section of two geocoded, atmospherically corrected, and co-registered HYMAP data acquisitions in Barrax. The chess-board-like pattern in the overlapping area is obtained by alternating squares in the north-south image, which is superimposed on top of the east-west image. Both images have been processed in the same way (calibration, geocoding/correction, atmospheric correction, image processing), and the differences are due solely to angular effects.

The angular effects are most pronounced in the hot-spot region (a bright horizontal band in the upper third of the image) and disappear in the nadir viewing direction (slightly below image centre). Images without any directional components would not exhibit any pattern-like structure. In this case, the hot spot in the east-west direction is not present in the north-south image. Also, no pattern-like structure can be

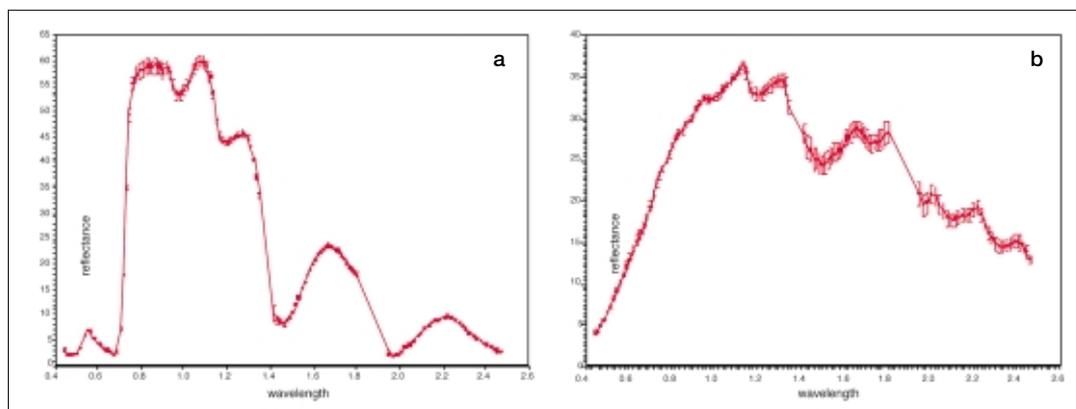
observed close to nadir in the centre of the image.

Figure 11b is an example of a new method for normalising hyperspectral images to a single viewing geometry (BRDF correction). The BRDF geometry takes place after geo- and atmospheric correction and a statistical method is used to extract BRDF measurements for each surface type. The Ambrals Model is applied to the data and correction factors are calculated. The procedure currently requires user supervision, but has the potential to be automated in the future.

As a result, most of the differences disappear in the right-hand image (Fig. 11b). Only some vegetated areas show residual differences, which are smaller than the original ones. These classes have a large internal reflectance variation. Improving the classification will reduce the errors. A prerequisite for separating a class is to have enough occurrences at different viewing angles within the image.

The ability to discriminate between green vegetation (Fig. 12a), senescent vegetation (Fig. 12b), and soil background is essential

Figure 12a,b. Spectral response of the HYMAP sensor for (a) green vegetation, and (b) senescent vegetation, for the Barrax study area during DAISEX '99



not only to retrieve critical biophysical parameters, but also for the assimilation of data into models describing the terrestrial carbon cycle, where the different roles of the green (photosynthetically active) vegetation, the senescent vegetation (carbon assimilation) and soil (mostly for soil respiration) must be properly accounted for.

Figure 13 compares actual HYMAP reflectance data, derived from raw data after calibration and atmospheric correction, and simulated reflectance data, by means of a theoretical radiative transfer code driven by elementary inputs describing the leaves, the soil background and the canopy structure. The good fit that has been obtained is an indication both of the accurate radiometric calibration and atmospheric correction of the HYMAP data, and the stability achieved across the whole spectral range. The fit also illustrates our present capabilities for modelling hyperspectral data by means of radiative transfer codes. The code is based on the scattering and absorption properties of elementary leaf constituents. The combined soil-canopy response is obtained by modelling the transport of photons across the medium. Any deficiency in the theoretical modelling and/or the calibration of HYMAP data would show up in this plot.

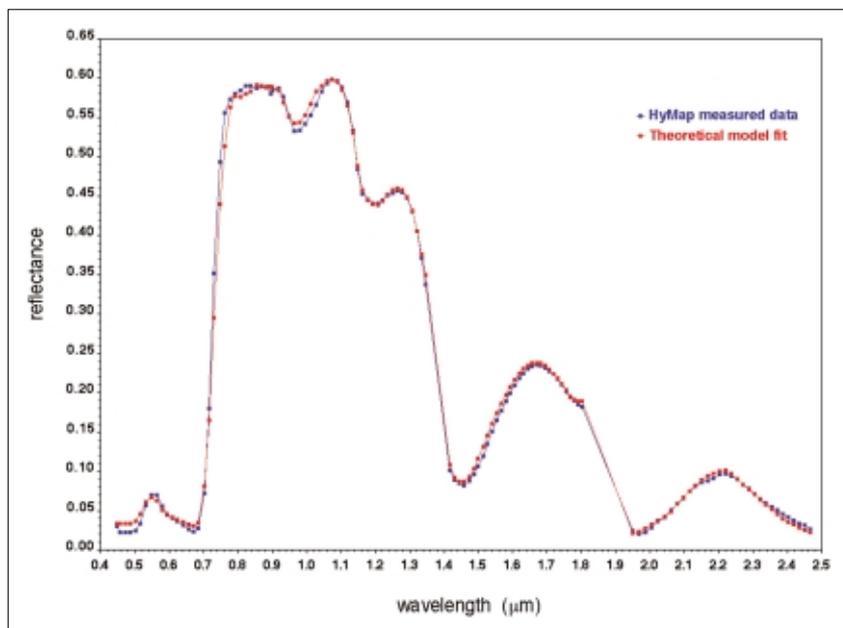
The ability to understand the theory behind the role of each individual variable in the combined spectral response finally measured by the sensor is important for retrievals of bio-/geo-chemical parameters and for assimilating hyperspectral data into models of land-surface processes.

Outlook

Data acquired during the DAISEX campaigns are currently being further analysed and validated. In particular, validation of higher-level products accounting for different viewing and illumination geometries will be analysed, by comparing measured and modelled BRDFs and by inverting a full radiative transfer code.

Results of the campaigns will be aggregated into process models describing the vegetation growth and energy/water balance over time. This will further demonstrate the feasibility of a future land mission aimed at advancing our knowledge of land-surface processes and interactions with the atmosphere.

A Workshop summarising the results is planned for the beginning of 2001. In addition, ESA plans to fund dedicated studies addressing some of the open questions discussed in this article by exploiting the data acquired during the DAISEX campaigns.



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Figure 13. Comparison between actual HYMAP reflectance data, after calibration and atmospheric correction, and simulated reflectance data by means of a theoretical radiative transfer code