

- EarthCARE** - Earth Clouds, Aerosols and Radiation Explorer
- SPECTRA** - Surface Processes and Ecosystem Changes Through Response Analysis
- WALES** - Water Vapour Lidar Experiment in Space
- ACE+** - Atmosphere and Climate Explorer
- EGPM** - European Contribution to Global Precipitation Measurement
- Swarm** - The Earth's Magnetic Field and Environment Explorers





*REPORTS FOR MISSION SELECTION*  
THE SIX CANDIDATE EARTH EXPLORER MISSIONS

**SPECTRA –  
Surface Processes  
and Ecosystem Changes  
Through Response Analysis**

***European Space Agency  
Agence spatiale européenne***

ESA SP-1279(2) – SPECTRA – Surface Processes and Ecosystem Changes Through Response Analysis

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## 1. Introduction

The ESA Living Planet Programme includes two types of complementary user driven missions: the research-oriented Earth Explorer missions and the operational service oriented Earth Watch missions. These missions are implemented through the Earth Observation Envelope Programme (EOEP) and the Earth Watch Programme, where the Earth Explorer missions are completely covered by the EOEP.

Earth Explorer missions are divided into two classes, with Core missions being larger missions addressing complex issues of wide scientific interest., and Opportunity missions, which are smaller in terms of cost to ESA and address more limited issues. Both types of missions address the research objectives set out in the Living Planet Programme document (ESA SP-1227 1998), which describes the plans for the Agency's strategy for Earth Observation in the post-2000 time frame. All Earth Explorer missions are proposed, defined, evaluated and recommended by the scientific community.

Following a call for Core mission ideas in 2000 and selection of five of the ten proposals for pre-feasibility study, three of the candidates, EarthCARE, SPECTRA and WALES, were chosen for feasibility study in November 2001. In response to a call for Opportunity mission proposals in 2001, which resulted in 25 full proposals being submitted by early 2002, three mission candidates, ACE+, EGPM and SWARM, were also chosen for feasibility study. The Phase-A studies for all six Earth Explorer candidate missions are being finalised by early 2004, forming the basis for the Reports for Mission Selection for all six candidate missions.

This Report for Mission Selection for SPECTRA was prepared based on inputs from the Mission Advisory Group (MAG) consisting of: F. Baret (INRA CSE, Avignon, France), B. van den Hurk (KNMI, de Bilt, The Netherlands), W. Knorr (Max-Planck-Institute for Meteorology, Hamburg, Germany), W. Mauser (University of Munich, Germany), M. Menenti (University Louis Pasteur, Illkirch, France), J. Miller (York University, North York, Canada), J. Moreno (University of Valencia, Burjassot, Spain), M. Schaepman (University of Wageningen, The Netherlands) and M. Verstraete (EC Joint Research Centre, Ispra, Italy). Parts of the Report have been prepared by the Executive based on inputs provided by the industrial Phase-A contractors. H. Dolman, T. Kaminski and all others, who participated in the supporting studies during Phase-A, are acknowledged for their direct or indirect contributions to this Report.

The Report for Mission Selection for SPECTRA, together with those for the other five Earth Explorer candidate missions, is being circulated within the Earth Observation research community in preparation for a User Consultation Meeting at ESRIN, Frascati, Italy, in April 2004.



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## 2. Background and Scientific Justification

### 2.1 The Scientific Context

During the last century CO<sub>2</sub> emissions have increased significantly because of fossil fuel consumption and land use change. Similar rates of increase in atmospheric concentration have not been observed during the last 420,000 years (Petit et al. 1999), and probably for much longer than that (Prentice et al. 2001). Anthropogenic emissions of greenhouse gases have already started to alter the Earth's climate (IPCC, 2001). The long-term stabilization of CO<sub>2</sub> levels in the atmosphere is therefore a major challenge to humanity, and one of the most important policy goals recognized by the United Nations through its Framework Convention on Climate Change (UNFCCC). Measurements of the rate of increase in atmospheric CO<sub>2</sub> and calculations of the global CO<sub>2</sub> budgets imply that a large fraction of emissions is being absorbed in terrestrial carbon pools and that current estimates put the biosphere sink at roughly half the emissions.

All process-based models of terrestrial carbon cycling, whether driven by climate change scenarios (Cramer et al. 2001, Prentice et al. 2001), or fully coupled to climate models (Cox et al. 2000, Dufresne et al. 2002), consistently show that this terrestrial carbon sink may not be sustained in the future. The sink strength, initially rising in line with emissions, is likely to saturate, and may even become a source in the course of this century. Large-scale land conversions may further reduce CO<sub>2</sub> uptake by the terrestrial biosphere.

The scientific community has responded to these findings by initiating a range of research programmes combining experimental and process-modelling approaches. To that end, no less than four Global Change Research programmes (WCRP, IGBP, IHDP and DIVERSITAS) within the Earth System Science Partnership have established the Global Carbon Project (GCP). The goals of this research (GCP 2003) can be summarized as follows:

- *diagnose* the current space-time patterns of terrestrial biosphere–atmosphere CO<sub>2</sub> exchanges
- *identify* and *quantify* the key underlying processes that govern the terrestrial CO<sub>2</sub> balance;
- *reduce uncertainties* in predicting the likely future course of the terrestrial carbon balance and finding possible points of intervention for carbon management.

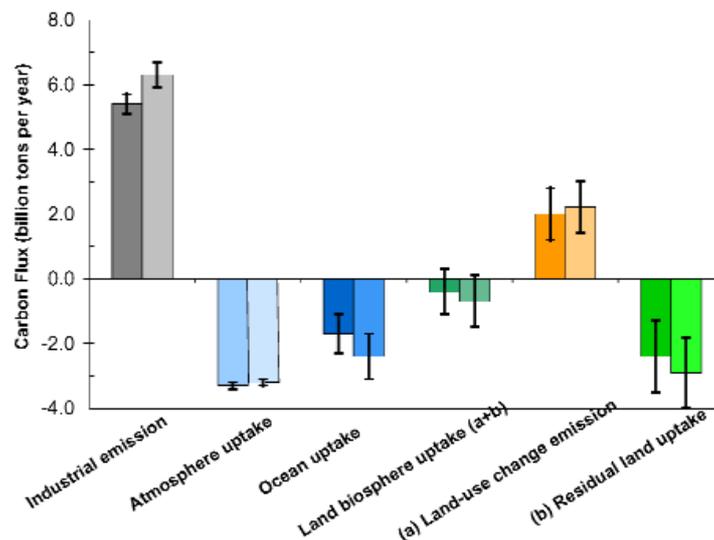
**The SPECTRA mission addresses these issues by providing detailed observations to help understanding the terrestrial component of the carbon cycle.**

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## 2.2 Current Understanding and Uncertainties

The fate of CO<sub>2</sub> within the Earth system, once released, is still poorly understood. From 1980 to 1989, fossil fuel burning, cement production and land use changes taken together have released about 7.4 billion tons of carbon (GtC/yr) into the atmosphere each year, 45% of which has contributed to increasing its CO<sub>2</sub> concentration. For the period 1990 to 1999, the emissions have increased to an estimated 8.5 GtC/yr, of which only 38% remained in the atmosphere. Nevertheless, atmospheric CO<sub>2</sub> concentration still rose at about the same rate as during the preceding decade (Joos et al. 2003). While estimates for emissions from land use change (at around 2 GtC/yr) are far from accurate (Houghton et al. 2003), both the atmospheric increase and emissions from industrial activities are well documented. It is thus well established that a combination of oceanic and terrestrial carbon uptake is preventing a much more rapid increase of atmospheric CO<sub>2</sub> levels.

Inversion studies using CO<sub>2</sub> concentration, isotope and oxygen-nitrogen ratio measurements (top-down approach) further indicate that the interannual variability of CO<sub>2</sub> fluxes is much higher for the terrestrial biosphere than for the oceans (Rayner et al. 1999). Recent estimates suggest that during the 1980s, 23% of total anthropogenic carbon emissions were taken up by the oceans, and as much as 32% by the terrestrial biosphere. For the 1990s the figures are 28% for the oceans and 34% for the land (Fig. 2.1) (Joos et al. 2003).



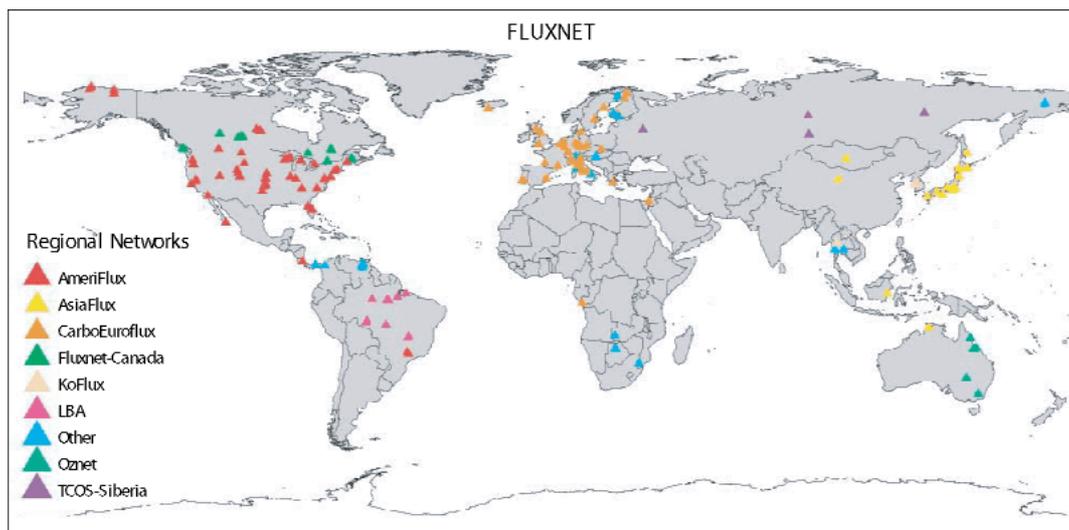
**Figure 2.1:** Exchange fluxes between the carbon pools, with the associated uncertainties (data taken from Joos et al. 2003). Data are for the periods from 1980 to 1989 (left bars) and 1990 to 1999 (right bars).

A fundamental question that has yet to be addressed in order to predict future trends in the carbon cycle is the identification of which processes dominate on what space and

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time scales. The processes governing the fluxes between the atmosphere and the terrestrial biosphere, as well as between the various terrestrial pools, take place at widely diverse rates and temporal scales, from daily to centennial and longer. Carbon fluxes in the biosphere are usually characterized as Gross Primary Production (GPP=primary CO<sub>2</sub> uptake by photosynthesis), Net Primary Production (NPP=GPP minus plant respiration, ca. 50% of GPP), Net Ecosystem Production (NEP=NPP minus soil respiration, ca. 5% of GPP), and Net Biome Production (NBP=NEP minus loss of carbon from natural disturbances and human impacts). To assess, understand and predict those fluxes requires both accurate observations and the development and application of process models.

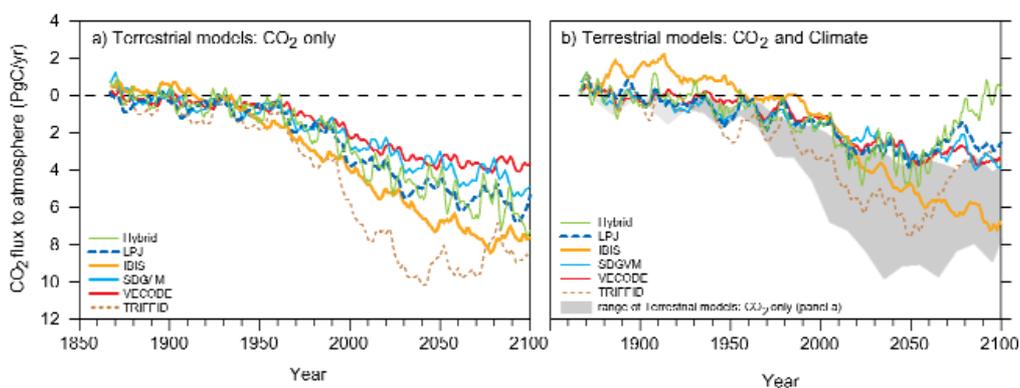
Current terrestrial carbon fluxes. Local CO<sub>2</sub> flux data, combined with other eco-physiological field measurements, provide vital information to understand processes like photosynthesis and respiration and to determine GPP and NEP. CO<sub>2</sub> concentration measurements can be exploited by inverse modelling techniques to infer the large-scale patterns of NBP. Land use and land cover change maps, often relying on remotely sensed information, are used to infer carbon stock changes from disturbance and regrowth, i.e. the difference between NEP and NBP. However, the existing flux measurement network is too sparse (Fig. 2.2), and the footprint of each flux tower is too small to extrapolate observations in a reliable and accurate way. Furthermore, inverse modelling gives broad spatial patterns only, while inventory data are often difficult to interpret. As a consequence, there is no systematic and convincing agreement between the various approaches to determine the spatial patterns of major fluxes in the carbon cycle. The current observational network is insufficient to determine carbon sources or sinks with acceptable accuracy at regional, continental or inter-annual time scales (Janssens 2003).



**Figure 2.2:** Geographical distribution of FluxNet sites (GCP 2003). Courtesy of Oak Ridge National Laboratory Distributed Active Archive Center, [<http://fluxnet.ornl.gov/fluxnet/map>].

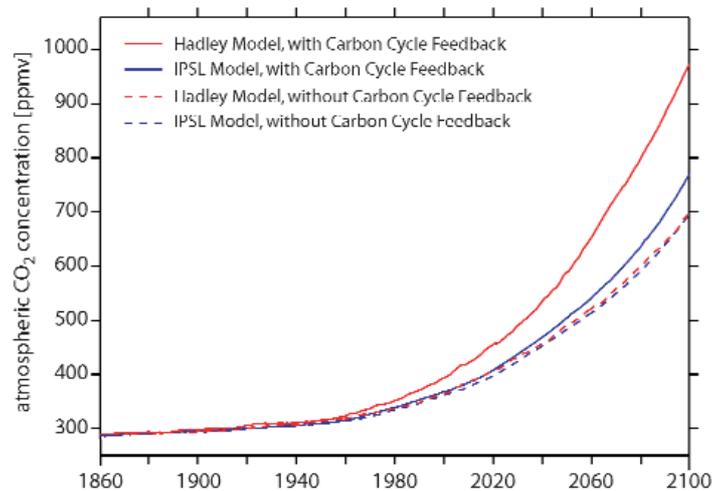
A fundamental problem with the existing network is that observations that are accurate enough to allow accurate parameterisation of process models are available at much smaller spatial scales than those that are relevant for the study of an intrinsically global problem. Global-scale terrestrial ecosystem models have typical grid sizes of 50 by 50 km, while ecosystem function is studied at scales from centimetres (e.g. leaf-level measurements, soil probes) to a few hundred metres (eddy covariance towers). A possible solution, recognised by many projects (e.g. EU projects AEROCARB, RECAB, TCOS-Siberia), is the use of tall towers and aircraft measurements. Here, the challenge when studying large-area NEP lies in attributing observed fluxes to the pattern of land cover within the very large footprint of observations. Understanding the causes and processes underlying fluxes at larger spatial scales requires the application of ecosystem models, but it remains challenging to determine accurately the values of the ecosystem process model parameters representative of the large footprint of tall towers. A significant source of uncertainty is that both vegetation and model properties are usually estimated from land cover maps established at much coarser spatial resolution, rather than measured. There is simply insufficient spatially explicit data available to allow the attribution of accurate process parameters to an entire region approximately the size of a global-model grid cell.

Future terrestrial carbon fluxes. The future contribution of the terrestrial biosphere as a buffer of anthropogenic fossil fuel emissions is presently unclear (Dolman et al. 2003). The apparent increase in the terrestrial uptake of CO<sub>2</sub> between the 1980s and 1990s, discussed above, has been documented at the global scale only, and identifying its causes remains a priority to reliably predict the strength of the future terrestrial carbon sink. A number of terrestrial ecosystem models driven by observed changes in CO<sub>2</sub> and climate indicate a trend towards higher uptake after 1990 (McGuire et al. 2001), in line with observations, but inter-model differences are still large.



**Figure 2.3:** Projections of anthropogenic CO<sub>2</sub> uptake (negative CO<sub>2</sub> flux) by six dynamic global vegetation models: (a) driven by changes of atmospheric CO<sub>2</sub> only, and (b) driven by changes in CO<sub>2</sub> concentrations plus the simulated evolution of climate obtained from the Hadley Centre climate model with CO<sub>2</sub> and sulphate aerosol forcing from IS92a (Prentice et al. 2001). Panel (b) also shows the envelope of the results from panel (a) (in grey) (Courtesy of IPCC).

Further simulation studies with a range of Dynamic Global Vegetation Models (DGVM), driven by both observed and predicted climate (Cramer et al. 2000), consistently indicate that rising CO<sub>2</sub> levels are causing a persistent, later saturating carbon sink, while the effect of climate change, itself caused by CO<sub>2</sub> rises, may lead to a reduction in sink strength or even in a source (Fig. 2.3). When one of the models (TRIFFID) that still predicted a terrestrial carbon sink for 2100 was fully coupled to a climate model (i.e. the response of the climate to vegetation changes was included), the result was a reversal of that sink to a carbon source around the year 2070 (Cox et al. 2000). Such predicted positive climate feedbacks, however, turned out to be highly model dependent (Fig. 2.4).



**Figure 2.4:** Simulated atmospheric CO<sub>2</sub> concentration with two coupled atmosphere-carbon cycle models (solid lines), and for uncoupled simulations without carbon cycle feedback (dashed lines) (after Friedlingstein et al. 2003).

There is clearly an urgent need for a better understanding of the underlying processes and removal of the causes of such large uncertainties, both in view of the implementation of global environmental policies and of predicting the long-term evolution of Earth's climate. Differences in the parameterisation of carbon exchange between vegetation, soil and atmosphere in existing Earth system models give rise to significant uncertainty in future climate predictions. Improving the parameterisation of these processes and interactions in global models requires documenting processes at appropriate spatial and temporal scales, over an ensemble of regions representing all terrestrial biomes, including their functioning and heterogeneity. **The current practice of determining biosphere parameters through local field measurements and using them directly in global models is not adequate, because it does not represent the biosphere at the appropriate scale.**

### 2.3 From Local to Global Scales

The observation of the dynamics of key vegetation properties (such as chlorophyll- and water content or temperature) enables us to infer the values of ecosystem model

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parameters (such as water and light use efficiency) that correctly represent the behaviour of terrestrial vegetation, its development, and spatial heterogeneity. **The SPECTRA mission is designed to provide information on the vegetation characteristics** at scales ranging from local to regional following the **common** practice to define spatial scales of biosphere processes:

*The local scale (10-100 m)* corresponds to the typical length scale of the internal variability of landscapes (Briggs et al. 1995). Depending on the biome, it also represents the largest scale at which all relevant environmental variables can be exhaustively documented in field studies. It is therefore the native scale of most dynamic vegetation models and corresponds to the typical scale at which human activities take place (e.g. agriculture, deforestation, afforestation, fires). **The SPECTRA mission will resolve the local scale explicitly.**

*The regional scale (10-100 km)* is defined here as the typical scale of variability of a representative landscape. At this scale, topography may play a dominant role in the transfer and storage of water with strong implications on vegetation functioning. This is also a useful scale to document the long-term evolution of spatial gradients, due to past disturbances, or to derive model parameterisations. For these reasons, **the SPECTRA mission will provide observations at the regional scale** to help develop robust, detailed Dynamic Vegetation Models over a representative ensemble of biomes and conditions.

*At the global scale*, the relevant spatial variability is driven by the distribution of land and oceans, as well as by that of biomes over the continents. Global assessments of the carbon cycle must necessarily rely on parameterisations of processes occurring at scales too small to be resolved in global models. These parameterisations may rely on a simplified representation of heterogeneity, e.g. by lumping the area covered by each vegetation type in a homogeneous tile and disaggregating a large model grid box into several tiles. The heterogeneity of the land surfaces is then taken into account by associating biome-specific parameterisations with a global biome distribution map. The SPECTRA mission will contribute to process understanding at this scale through the improved parameterisations developed as a result of detailed studies at the regional scale. **The SPECTRA mission will rely on an ensemble of regions that sample the range of biomes and conditions over the Earth.**

#### **2.4 Observation of the Terrestrial Biosphere from Space: the Delta of SPECTRA**

There is a clear knowledge gap between what is known empirically through local measurements and the abstractions inherent in the parameterisations used in global models. A robust and scientifically sound strategy to fill this gap will require a focussed observational, experimental and modelling strategy covering an ensemble of regions, representative of all relevant terrestrial biomes, and the development of suitable parameterisations for each one of them.

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Remote sensing from space can complement field investigations by offering unique capabilities to address spatial scaling issues, provided these observations are acquired at the appropriate spatial, temporal, spectral and directional resolutions. Current medium resolution satellite sensors such as MODIS, MISR, MERIS and AATSR are capable of observing the global phenology of terrestrial vegetation (e.g. Potter et al. 2003). However, these observations are inadequate to characterise the spatial variability and non-linearity of biosphere processes, owing to their limited spatial, spectral and directional resolutions.

The SPECTRA mission will collect detailed observations for all relevant major biomes, and generate products such as albedo, leaf area index, fraction of photo-synthetically active radiation, vegetation cover fraction, leaf chlorophyll, water and dry matter content, leaf and soil temperature and the fraction of living/dead biomass.

SPECTRA's high accuracy and spectro-radiometric measurements will provide the means to improve the representation of spatial variability and non-linearity of biosphere processes in global biosphere and climate models. The primary objective of the SPECTRA mission is to bridge the gap between observations at the local scale and model parameterisations at the regional scale, leading to a robust description of biospheric processes at the global scale.

The terrestrial carbon cycle community is moving towards higher spatial and temporal resolution in both its observational and modelling efforts. SPECTRA will enable the carbon cycle, ecosystem and climate modelling communities to relate crucial knowledge from the local scale to the relevant regional scales that are key to understanding and predicting climate change and trends in terrestrial carbon fluxes and stocks. By providing a broad range of accurate ecosystem information at a scale comparable to the local measurements of flux towers, it provides quintessential information with which to extrapolate process knowledge to global scales. This will enable global models to be tested and improved much more rigorously than is currently possible, and therefore increase our understanding of the terrestrial component of the global carbon cycle.



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### **3. The SPECTRA Research Objective**

The prime scientific objective of the SPECTRA mission is to make a major contribution to the description, understanding and modelling of the role of terrestrial vegetation in the global carbon cycle and its response to climate variability under the increasing pressure of human activity.

The SPECTRA mission will contribute to the systematic description of the accumulation and transformation of biomass in response to environmental forcing at scales ranging from local (10 - 100 m) to regional (10 - 100 km). SPECTRA will provide detailed, repeated remote sensing observations suitable for characterizing the vegetation properties at a large number of key sites, selected to document the distribution and variability of natural and managed terrestrial environments. These space-based measurements, together with simultaneous, coordinated local field observations, will be useful both for characterizing these environments and for improving their parameterisations in dynamic climate and ecosystem models operating at broader scales, where the details of individual processes cannot be explicitly represented. This upscaling approach will ultimately result in more accurate, robust assessments of the terrestrial component of the global carbon cycle.

Multiple spectral and directional observations of vegetation reflectance constrain the retrieval of accurate environmental variables and enable the development of better parameterisations of biosphere processes. The scientific outcome of the mission will thus include both an improved understanding of the dynamics of the major global biomes, and a better ability to predict their evolution.

The SPECTRA mission aims to:

- deliver accurate estimates of vegetation distribution, structural and biogeochemical properties at the regional spatial scale, with a temporal resolution sufficient to characterise the evolution of individual vegetation types
- bridge the gap between the variety of field measurements (including gas fluxes) and regional and global assessments of the carbon balance
- provide quantitative information suitable to represent the structure and functional heterogeneity of the terrestrial biosphere in global scale models
- generate a better understanding of the role and function of vegetation structure and heterogeneity in terrestrial landscapes, for a wide variety of environmental conditions and anthropogenic influences.

The SPECTRA mission will measure radiative properties that will be interpreted in terms of local biogeophysical variables at the full resolution of the sensor. The latter will, in turn, be exploited to parameterise models at larger spatial scales.

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The Terrestrial Observation Panel for Climate (TOPC) has identified the need to observe more than 80 terrestrial variables to fully characterize the climate system (GCOS 82, April 2003). These key properties are state variables that relate to different processes. In the case of the DGVMs that are used to describe the terrestrial carbon cycle and predict its evolution, the main processes include photosynthesis, respiration, evaporation from soil and transpiration by vegetation. These exchange processes are controlled by canopy structural and energy balance variables: the temperature of the vegetation and the soil, the albedo (controlling the amount of available radiative energy) and the fraction of absorbed photosynthetically active radiation (fAPAR). The leaf area index (LAI) is the structural variable that plays a dominant role in these processes. In addition, the biochemical composition of the leaves (including chlorophyll, water and dry matter content) plays a major role. Phenology, allocation of biomass to the different organs (leaves, trunks, fruits, roots), and finally senescence constitute the response of vegetation to climate at the seasonal time scales.

The SPECTRA mission will provide estimates of these essential vegetation properties with sufficient accuracy to provide useful constraints on model variables in data assimilation procedures. The selection of the properties is based on the role the variables play in the key vegetation processes, which can be summarized as follows:

*Canopy structural and energy balance variables:*

- **albedo** controls the fraction of irradiance that is reflected by the surface. It can be defined as the hemispherical reflectance integrated over the whole solar spectrum domain (300-3000 nm) or split into spectral sub-domains to get a more accurate description of energy partitioning.
- **fCover** is the fraction of vegetation coverage as seen from nadir. It determines the partitioning of radiation between the soil and vegetation canopy.
- **fAPAR** is the fraction of radiation that is absorbed by the live green vegetation elements in the photosynthetically active radiation domain (400-700 nm).
- **Leaf area index (LAI)** is the green leaf area per unit horizontal area. It defines the actual size of the interface between the vegetation and the atmosphere. It has a pronounced annual cycle and depends on the vegetation phenology.
- **Temperatures of soil and vegetation** result from the balance between absorbed and released energy. They have been widely used to study and monitor the water balance of the vegetation and underlying soil. They are also important drivers for photosynthesis and respiration.

*Vegetation biochemical variables:*

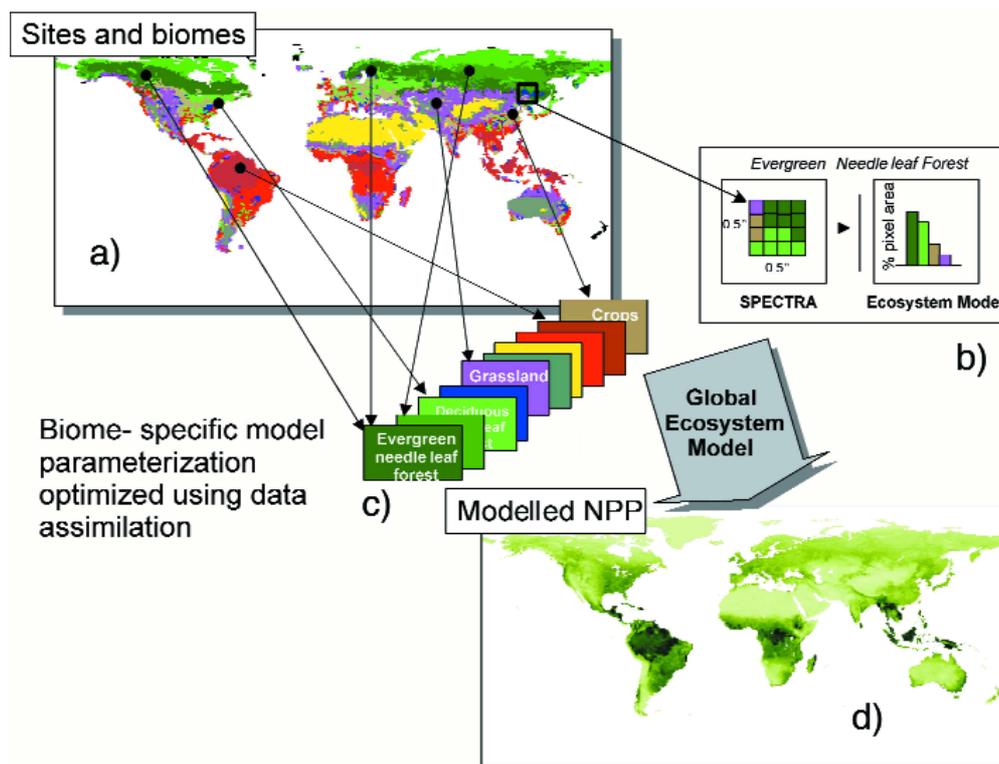
- **Chlorophyll** is the chemical component responsible for photosynthesis. Its concentration therefore controls primary productivity. Leaf chlorophyll content

(expressed in mass per unit leaf area) is regulated by the leaf nitrogen content, which is an important driver of vegetation growth.

- **Leaf water content** varies with the water status of plants and age of the leaves. It is expressed as the mass of water per unit leaf area.
- **Leaf dry matter content** (mass per unit leaf area) is a key variable in vegetation growth that is directly related to biomass allocation.
- **Fraction of dead biomass** describes the dynamics of the senescence process.

Each SPECTRA data set will consist of time series of estimates of these variables over a spatial domain consistent with that used within DGVMs. This spatial extent is considered sufficient to capture the characteristic regional vegetation composition, structure and functioning (Fig. 3.1).

A sufficient number of samples will be acquired over all terrestrial biomes during the lifetime of SPECTRA to represent the global functioning and dynamics of vegetation.



**Figure 3.1:** Information flow from SPECTRA observations to global modelling of carbon cycle: (a) SPECTRA provides observations of an ensemble of sites designed to sample all biomes and document spatial variability within each one; (b) regional Dynamic Vegetation Models are implemented at high spatial resolution to assimilate SPECTRA observations; (c) biome specific parameterisations of biosphere processes are developed; (d) the biome specific parameterisations are implemented in global carbon models to estimate current and future patterns of NPP (Courtesy of G. Churkina).

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The SPECTRA measurements close the gap between very accurate local observations of plant canopy properties on the one hand, and models of global biosphere processes on the other. The observations of plant canopy properties will be used to constrain regional ecosystem models to obtain better estimates of model parameters and their spatial variability within each observed biome. These improved parameters can then be used in global models of the atmosphere – ocean – terrestrial biosphere system. The SPECTRA mission will therefore clarify the role of vegetation in the terrestrial carbon cycle. Also, it will determine its response to climate variability on seasonal to inter-annual time scales. The main scientific progress will result from the new level of global availability, accuracy and consistency of observed structural and functional vegetation properties.

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## **4. Observational Requirements and Measurement Principles**

### **4.1 Introduction**

The architecture of terrestrial vegetation and the biochemical composition of canopy elements, as described by the key variables listed earlier, are known to determine an information-rich radiance field in the optical (visible, near- and mid-infrared, as well as thermal infrared) region of the spectrum. Furthermore, since land surfaces are always observed through the atmosphere, and since these two geophysical media interact significantly, the proper interpretation of radiation measurements made by this mission must take full account of the many scattering and absorption processes that take place in this complex coupled geophysical system. The optimal way to address this complexity is to make full use of the directional and spectral signatures of this coupled system, by acquiring directional spectral measurements and analysing those with suitable models (Martonchik et al. 1998).

Some of the geophysical variables of interest, such as radiative fluxes or surface albedo, correspond to integral quantities; they can be estimated directly from the radiation measurements, provided a sufficient number of representative observations are acquired. All other biophysical variables are derived from a further detailed analysis of the spectral and directional signatures of the observed radiance fields. Radiometric observations exhibit useful variability in five domains (spatial, temporal, spectral, directional, and polarimetric), each of which could be exploited to retrieve information on the geophysical medium being observed.

### **4.2 Retrieval of Vegetation Properties from Space: Science Background**

#### **4.2.1 Reflectance and Emittance Anisotropy**

All radiometric measurements acquired with imaging sensors in the solar and thermal spectral range depend strongly on the zenith and azimuth angles of the light source and of the observer.

The processes responsible for the scattering of solar light in the atmosphere, its reflectance at the underlying surface, or the emission of thermal radiation by soils and plants are characterised by the Bi-directional Reflectance Distribution Function (BRDF) or by the Bi-directional Temperature Distribution Function (BTDF) of the observed target. These functions are spectrally variable and evolve with time; they carry information on the nature, structure and properties of the observed geophysical media. The angular signature can be exploited to improve the accuracy and reliability of products derived from other data, for instance by providing a much better characterisation of the reflectance anisotropy and of the overlying atmosphere.

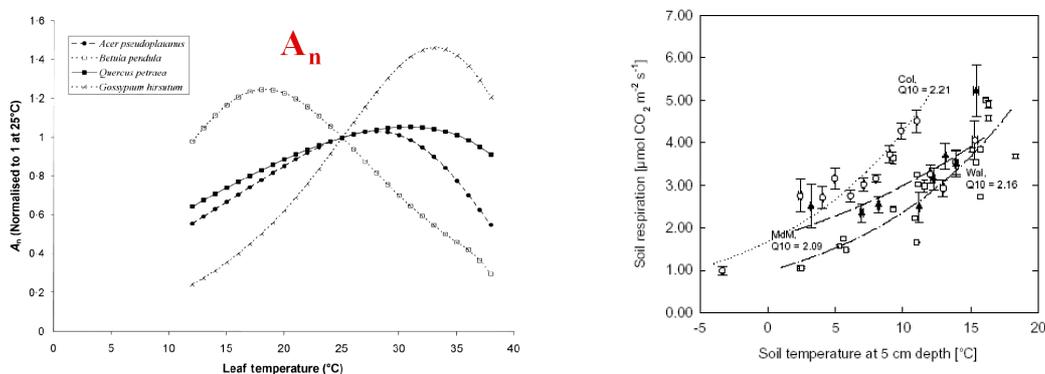
## 4.2.2 Spectral Variability

In the spectral range where radiative forcing is provided by the Sun (300 nm – 3000 nm), biochemicals present in vegetation and soils absorb radiation at specific wavelengths.

The published scientific literature confirms that spectral reflectance measurements from land targets are information-rich. The number of known relationships between vegetation or soil elements and spectral features is rather large. This is particularly evident when considering sharp and well-defined spectral features of vegetation, such as the so-called red-edge, due to strong absorption by chlorophyll in the red and the reflection of incident radiance by the plant in the NIR. Here subtle changes in the shape and position of the absorption band can be related quantitatively, as shown later, to key vegetation properties such as chlorophyll content. Accurate and continuous sampling of spectral reflectance within each absorption band is necessary to exploit these relationships.

Leaf water content can be retrieved by analysing specific spectral absorption bands of liquid water, particularly in the SWIR. High spectral resolution allows measuring directly the depth of the absorption bands, even for several absorption features across the spectral range. With a good spectral resolution and spectral stability, the shape of the absorption bands can be fitted to the expected theoretical behaviour of bound liquid water. Water content can then be retrieved with a high accuracy and robustness. An evaluation of this approach was presented by Moreno (2001) on the basis of both modelled and actual hyperspectral data.

Due to the strong temperature dependence (Fig. 4.1) of both leaf photosynthesis and soil respiration, foliage and soil temperature must be observed. In the thermal infrared region, where the radiative sources are the constituents of the Earth's surface itself and the atmosphere, a minimum of two spectral bands is required to establish the brightness temperature of the surface, taking atmospheric influences into account.



**Figure 4.1:** Carbon fluxes and component soil and foliage temperatures: (left) relative net photosynthesis,  $A_n$  (normalized to the observed value at 25°C), vs. foliage temperature (Medlyn et al. 2002); (right) soil respiration vs. soil temperature (after Matteucci et al. 2000).

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The acquisition of these measurements at multiple angles will allow decoupling of observations from background soil and overlying canopy temperatures (Menenti et al. 2001a). Measured radiances in the thermal domain depend on both the temperature and the emissivity of the emitting bodies. The latter may be quite variable spectrally over land targets, although to a lesser extent in the atmospheric window (10-13  $\mu\text{m}$ ). This choice simplifies significantly the analysis of spectral measurements in this spectral region.

### 4.3 Overview of Requirements

#### 4.3.1 Angular Requirements

Although a full characterisation of the anisotropy of the coupled surface atmosphere system may require many angular observations, a minimum of seven observation angles distributed as follows is required (ESA 2001):

- **One observation angle is required at or as close as possible to nadir** (in the case of across-track de-pointing) because this setup provides the best spatial resolution and the shortest atmospheric path length.
- **Four observations at large zenith angles (two in the forward and two in the backward scattering regimes)**, nominally at  $\pm 60^\circ$  and  $\pm 50^\circ$  relative to the surface reference ellipsoid, are necessary to sample the rapid changes in directional reflectance (BRF) or emittance (BTF). Observations at zenith angles of exactly  $60^\circ$  permit measurements through twice the atmospheric (and canopy) path length at nadir. The other pair of measurements not only serves to characterize the rate of change of BRF or BTF at those angles, but also helps in assessing the degree of asymmetry in the reflected or emitted fields, and thus permits one to differentiate the anisotropy of the underlying surface from that of the atmosphere, thereby allowing better atmospheric corrections.
- **Two other additional observation angles** are required, one on each side of the near-nadir observation mentioned above, to further improve the characterisation of the BRF/BTF, especially with regard to particular features such as the hot spot and specular reflectance. Since the angular position of these anisotropic features is tied to that of the Sun, which is variable in space and in time, these observation angles must be programmable as a function of the site observed and season of the year.

Several theoretical and empirical studies, as well as a substantial body of empirical evidence collected by existing multiangular sensors such as ATSR, POLDER and MISR, have amply demonstrated the usefulness of anisotropy observations for characterising both land surfaces and the overlying atmosphere in the solar domain.

Because of the high sensitivity of both reflectance and emittance to the observation zenith angle, it is critical that the knowledge of the actual measurement angles be very precise, i.e. within better than  $1^\circ$  of their actual values. This is particularly important at

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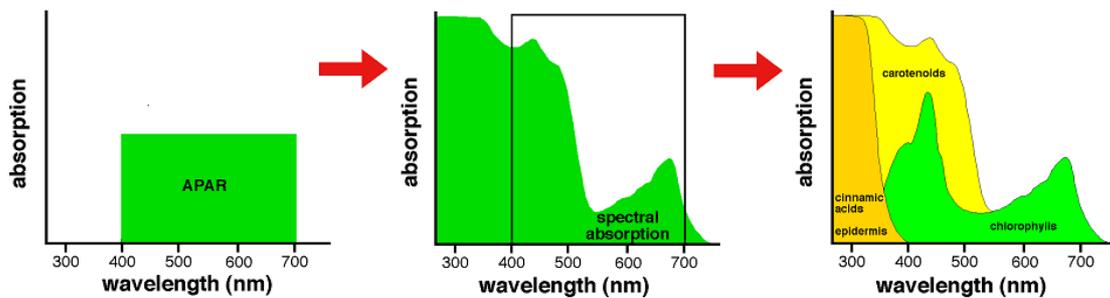
large observation zenith angles, where small errors in angular pointing result in large variations in optical paths and positions on the ground.

The anisotropy of land surfaces varies with wavelength. It is thus necessary to acquire these directional measurements hyperspectrally. Limited empirical evidence is currently available in that area, because the directional observations in a large number of spectral bands are not being readily acquired from space or from airborne sensors for the required spectral range.

### 4.3.2 Spectral Requirements

The delivery of reliable, accurate, quantitative estimates of specific biogeophysical variables will be met by acquiring dense contiguous observations in the spectral range between 400 and 2350 nm. These spectral regions include:

- (1) the 400-700 nm region where leaf pigments absorb sunlight and determine photosynthesis (Fig. 4.2)
- (2) the ‘red edge’ exhibited by vegetation in the region 650-800 nm through chlorophyll
- (3) the NIR spectral region (850-1050 nm) where liquid water and water vapour absorption bands are sufficiently separated to be distinguishable
- (4) the SWIR (1330-2400 nm) region carrying information on organic matter, soil and leaf composition (Fig. 4.3).

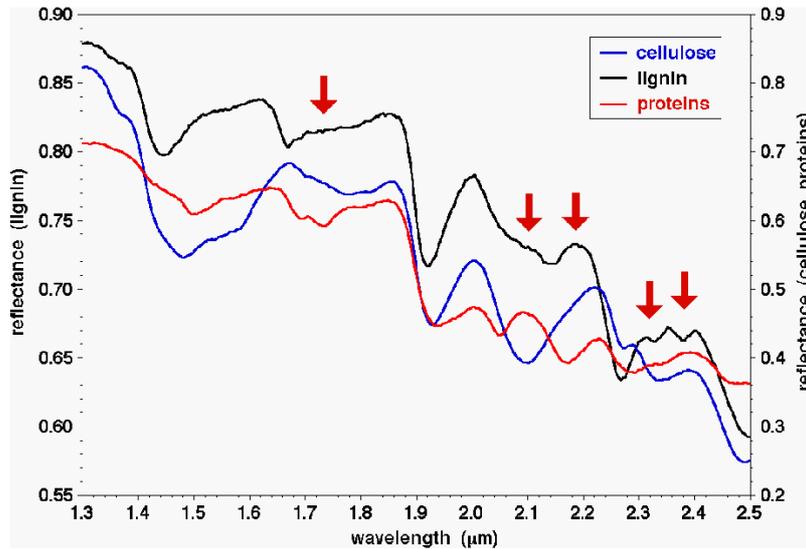


**Figure 4.2:** Different approaches in describing light absorption by leaf pigments in carbon assimilation models: (a) conceptual, purely empirical approach; (b) effective light use efficiency concept; (c) explicit description of absorber amounts (Courtesy J. Moreno).

Airborne spectroscopy has clearly demonstrated the significant advantage of acquiring observations with a sound spectral coverage, at least in some specific parts of the spectrum. For instance, Boardman and Green (2000) analysed the spectral variability of a series of 510 data sets, acquired with the AVIRIS airborne sensor at a spectral resolution of 10 nm. The dimensionality of the datasets was evaluated at around 60 dimensions on average.

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A user selectable subset of a least 60 spectral bands in the solar spectral domain of the entire VIS, NIR, SWIR spectrum, plus the two normal bands, should thus be provided for all the observation directions.



**Figure 4.3:** Laboratory measurements of spectral reflectances of samples of leaf cellulose, lignin and proteins in the SWIR spectral region (Courtesy J. Moreno).

Current experience with field and airborne instruments suggests that a Full Width at Half Maximum (FWHM) of the individual band pass of 10 nm is adequate to resolve most of the features of interest over land surfaces in the 400-2400 nm spectral range. In any case, whenever multiple contiguous spectral bands are required, the FWHM should not exceed 15 nm.

Accurate knowledge of the position of the bands is critical for the retrieval of the vegetation biochemical variables (Chapter 3), and the accuracy of the knowledge of wavelength position must be better than 1 nm in the solar spectral region.

In the thermal infrared (TIR), observed spectral radiance is determined by both target temperature and emissivity. The separation of temperature and emissivity is further complicated by the spectral dependence of emissivity, although this complication is much less severe in the spectral range 10-13  $\mu\text{m}$  than at shorter wavelengths. This is therefore the preferred spectral region for estimating surface temperature (Coll et al. 2000).

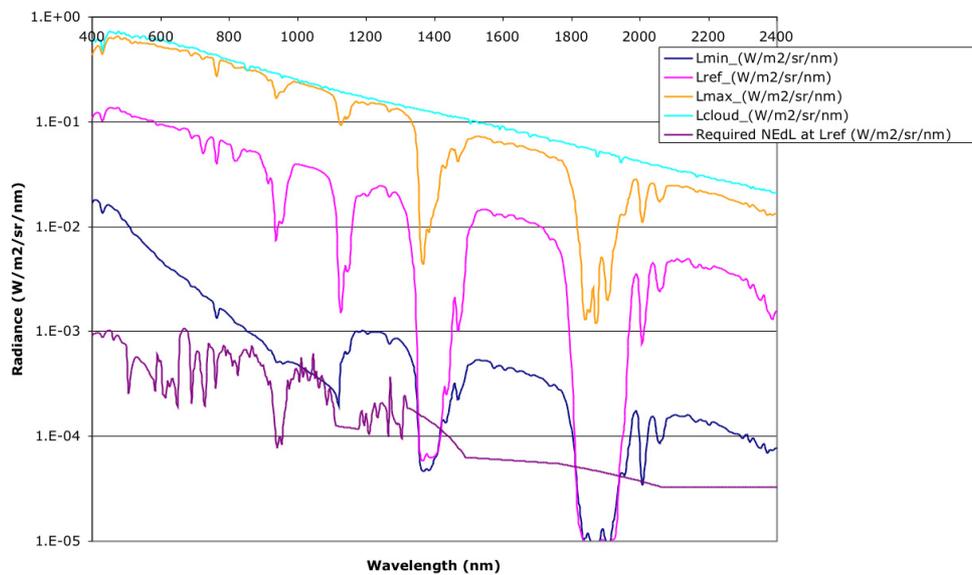
Current (so-called ‘split-window’) algorithms require a minimum of two spectral bands in the thermal infrared to retrieve surface temperature. This is because the atmosphere absorbs thermal radiation to a measurable extent, even in the atmospheric window. Thus, two spectral bands, positioned around 10.5-11.5  $\mu\text{m}$  and 11.5-12.5  $\mu\text{m}$ , respectively, are considered optimal for the determination of surface temperatures. The FWHM should be close to 0.5  $\mu\text{m}$ . These measurements must be acquired

simultaneously for the same geographical locations, and so the thermal spectral measurements must be co-registered. Given the spectral variability of atmospheric absorptions and of emissivity, the actual position of the thermal bands needs to be known to better than  $0.1 \mu\text{m}$ .

### 4.3.3 Radiometric Requirements

#### *Solar domain*

Studies conducted for the preparation of this mission (e.g. ESA 2001) show that the radiometric accuracy must be better than 3% absolute accuracy, and better than 1% band-to-band relative accuracy to be able to exploit differential absorption over almost contiguous bands. These requirements have been transformed into noise equivalent radiance at the sensor level, NEdL for a reference case (Fig. 4.4).



**Figure 4.4:** Modelled ranges of top-of-atmosphere (TOA) spectral radiances and required radiometric resolution: Minimum, Reference, Maximum and Cloud radiances were evaluated for a range of atmospheric and geographical situations to be expected during mission operation. The reference radiance is based on spectral reflectance typical of forest and forward modelled to TOA radiance; NEdL is derived on the basis of changes in TOA radiances due to changes in spectral reflectance of different surface types.

The maximal, and minimal radiances values under which SPECTRA should be used have also been computed. This corresponds to a large range of radiance levels required to avoid saturation (snow, clouds) and simultaneously giving the chance to work at low illumination (low Sun zenith angle) and in dark areas (dense coniferous forests). (Schläpfer and Schaepman 2002, Schaepman et al. 2001).

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The polarization sensitivity and the polarization dependent loss in the instrument have to be limited in such a way that their contributions remain a marginal source of uncertainty.

### ***Thermal domain***

The radiometric requirements for the thermal channels are conceptually less complex than for the reflectance channels (VNIR/SWIR). The dynamic range is set at 240-345 K. Studies show that the accurate retrieval of ground and vegetation temperatures (as well as of longwave fluxes) requires a radiometric resolution better of than 0.1 K with an absolute accuracy of better than 1.0 K depending on the temperatures (Caselles et al. 1996). The most relevant range for biosphere processes is 270-345 K.

The radiometric requirements can thus be summarized as follows:

- Radiometric measurements in the 400-2350 nm range must have the radiometric resolution (NE<sub>dL</sub>) indicated in Figure 4.4.
- The mission must provide TOA brightness temperatures with a radiometric resolution (NE<sub>dT</sub>) of better than 0.1 K when observing a black body at 300 K. The absolute BOA accuracy should be better than 1.0 K at 300 K.
- The polarisation sensitivity and the polarisation dependent loss in the instrument have to be limited in such a way that their contributions remain a minor source of uncertainty.

### **4.3.4 Spatial Requirements**

Many current process modelling studies of land biomes tend to assimilate either radiometric observations directly or biogeophysical variables. This requires integration of ecosystem and radiation transfer (RT) models, and a high degree of consistency in modelling the spatial organisation of landscapes. Therefore, assimilation of either radiometric observations or of retrieved variables requires a spatial resolution that is high enough to capture homogeneous samples of land cover types.

The spatial requirements can be summarised as follows:

- The mission must be able to provide data simultaneously acquired over target areas of about 50 km x 50 km.
- The mission must be able to provide data for individual areas smaller than a hectare and with a spatial sampling interval of about 50 m at nadir.
- The spatial width of each pixel should be as constant as possible over the full range of zenith angle acquisitions.
- The mission must be able to provide data for any terrestrial site at a latitude of up to 80°.

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The SPECTRA mission will take place in the context of many other existing or planned missions, which will also provide data relevant for the same geographical regions of interest. The proposed spatial resolution is complementary to those available from global Earth observing instruments, which typically operate at spatial resolutions between 250 and 1000 m, and bridges the gap (with respect to spatial resolution) between these and high-resolution instruments.

#### **4.3.5 Temporal Requirements**

Vegetation growth and development occur on time scales of a week or longer. The rate of change obviously varies significantly, but experience built upon field observations in major biomes leads to the conclusion that at least one observation per week is adequate, even during periods of rapid vegetation growth. Much more critical for the success of the mission is the time required to acquire a full set of angular observations. To be usable, all measurements must be made under constant target and atmospheric (not overcast) conditions. A total duration of 10 minutes for the acquisition of the required seven angular samples should not be exceeded in order to minimize potential changes in target and atmospheric conditions.

The temporal requirements are:

- The mission must be able to provide data for a minimum period of three years, with a desired lifetime of five years.
- The mission must be able to acquire data once a week for periods of up to a few months for any given site.

The relation between retrieval accuracy and sampling of the spectro-directional radiance field has been investigated during mission preparation (Verhoef and Menenti 1998, Menenti 2001b). These studies were done by evaluating retrieval accuracy for a large number of combinations of vegetation properties, atmospheric conditions and sampling schemes in the spectral and directional dimensions. Estimation errors were determined by means of numerical simulations.

The arguments developed in this chapter lead to the instrument requirements summarised in the following Table 4.1. The technical aspects of the SPECTRA mission fulfilling above requirements are detailed in the Technical and Programmatic Annex.

#### **4.4 Mission Elements**

The research objectives outlined in Chapter 3 and the observational requirements lead to a mission concept in which a space-borne imaging spectrometer acquires directional measurements over well-characterised sites, with a pre-determined temporal revisit sequence. The mission comprises three key elements:

Dimension	Mission Parameter	Value
Spatial	Size of scenes	50x50 km <sup>2</sup>
	Spatial sampling	50-100 m
	Registration accuracy	Knowledge Better than 0.2 pixels between bands, directions and dates
	Spatial coverage	Routine monitoring of 50 to 100 sites globally distributed
Temporal	Revisit frequency	2-3 days
	Time of overpass	Minimize cloud, maximize illumination; night observations in the thermal domain
	Duration of directional cycle	Acquisition at the 7 prescribed view angles should be as quick as possible and shorter than 10 minutes
Spectral	Spectral coverage	400-2400 nm (solar); 10.5-12.5 μm (thermal)
	Spectral resolution	10 nm (solar); 0.5 μm (thermal)
	Spectral calibration	Knowledge better than 0.5 nm (solar); 0.1 μm (thermal)
Directional	BRDF, BTDF sampling	Seven angles in the range ( $\pm 60^\circ$ ) as close as possible to the principal plane, avoid hot-spot
Radiometric	Radiometric accuracy	Solar: NEdL presented in Figure 4.4 Thermal: 0.1K relative accuracy, 1 K absolute at 300 K
	Range	Solar: defined in Figure 4.4 Thermal: 240-345 K

**Table 4.1:** Summary of SPECTRA mission requirements.

- **Field Segment:** well-documented and instrumented sites, intensively studied by the teams devoted to the scientific investigation of land-surface processes; this mission element implements the sampling of terrestrial biomes described in Chapter 2 (Fig. 3.1).
- **Space Segment:** a single satellite with an imaging spectrometer, providing observations of the selected sites and according to the requirements stated in Chapters 3 & 4.
- **Ground Segment:** satellite operations control and provision of data products.

A detailed description of the Mission Elements can be found in ESA (2001). The Field Segment is an innovative element of a space mission and is briefly described below.

The SPECTRA mission provides global access with high spatial, temporal, spectral and angular resolution data. The mission will focus on obtaining frequent data over an ensemble of regions, comprising research sites where intensive experiments and monitoring are carried out. The approach for integrating local measurements and the SPECTRA observations through data assimilation at the regional and global scale will be described in Chapters 5 and 6.

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It is safe to assume (ESA 2001) that a sufficient number of representative sites are available throughout the mission lifetime, because of the emergence of intensive, long term ground measurement sites that have evolved as a major feature of land science over the past two decades. The existing network of sites, mainly initiated and organised through the IGBP programmes and WCRP GEWEX, is developing data standards, lists of key variables and data sharing policies. Network hubs provide data standards, formats and shared data sets, as well as supporting inter-calibration and synthesis. SPECTRA would extend the capabilities of network-based research by providing time-series of key variables for regions surrounding intensively monitored sites. The typical site in the proposed SPECTRA network includes micro-meteorological measurements of sensible and latent heat, carbon dioxide and, in some cases other scalars such as ozone or non-methane hydrocarbons. Many of the sites include Sun-photometers and many participate in AERONET for aerosol measurement. Micro-meteorological measurements are typically complete, including air temperature, rainfall, wind-speed and direction, and in many cases soil moisture. Basic ecosystem measurements such as leaf area, biomass, soil carbon, nutrient cycling and litter fall are normally made. Some sites are linked to watershed studies and include lysimeter and stream-flow measurements. Increasingly, sites are making canopy architecture, leaf optical property, reflectance and light interception measurements, which are useful in testing and developing algorithms for satellite sensor retrievals.

While the exact distribution of sites worldwide that will be funded and operational at launch can not be identified at this time, the international commitment to site networks is strong and their scientific value is clear. In most cases, it has been evident that the value of well-chosen sites increases as their time-series of data get extended (Knapp and Smith 2001). It is thus expected that many of today's sites will continue to be used.

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## 5. Data Processing Requirements

This Chapter gives an overview of the conceptual steps that need to be implemented to obtain the required information from the SPECTRA observations. The assessment of the potential gain of using the SPECTRA observations in global monitoring or modelling studies is described in Chapter 6.

### 5.1 Pre-Processing

The first stage of data processing includes the following activities:

- Radiometric calibration: the process of converting the raw data into radiance measurements.
- Spectral calibration: the process of certifying the spectral location of the measurements.
- Co-registration: the process of ensuring that measurements obtained under different observing conditions (along-track and across-track depointing) and in different spectral regions can be located with sufficient geographic precision to allow data analysis for well-defined locations.

Other important steps include the confirmation of the angular conditions of observation, the precise timing of the measurements, etc. The end-result of these engineering activities is the creation of a data set containing all the calibrated, co-registered spectral and directional measurements obtained for a single scene. This data set is known as Level-1C. The rest of this Chapter is concerned with the definition of algorithms and processing methods to derive variables and processes occurring at the terrestrial surface of interest from the Level-1C products.

### 5.2 From TOA Radiometric Data to Canopy Variables

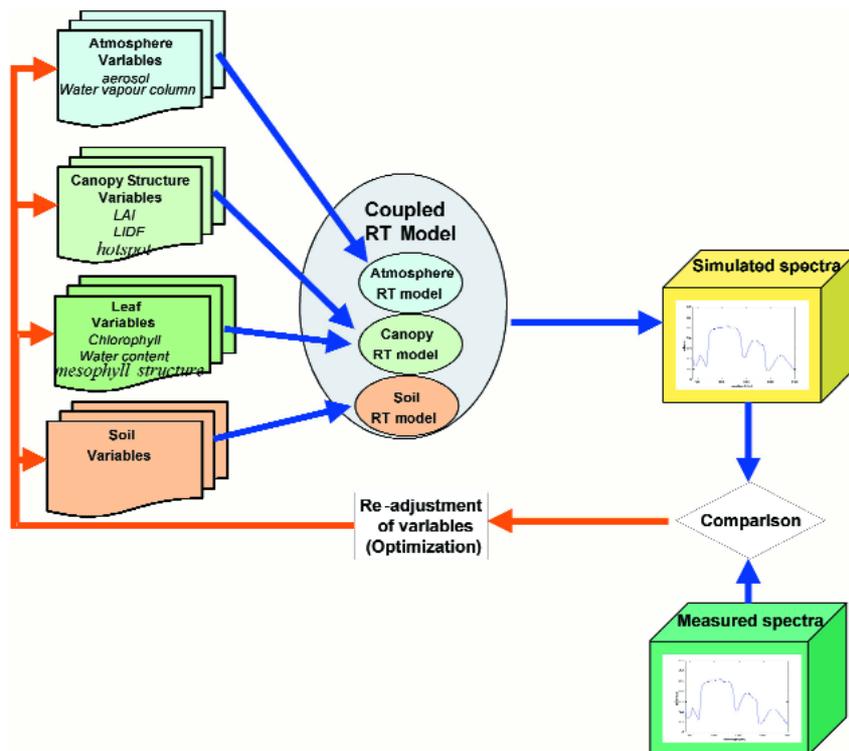
#### Algorithm Principles

All approaches for retrieving bio-geophysical variables from spectro-directional radiometric data rely on one or more models. The models can be explicit, as in the case of radiation transfer models, or implicit, as for vegetation indices, which imply underlying assumptions (Verstraete and Pinty 1996, Menenti et al. 2001a, Jia et al. 2003). In any case, models provide a link between the radiometric data and the variables and processes controlling these observations (Fig. 5.1). These models must take into account, for instance, the architecture of plant canopies, the properties of the plant elements and of the soil, as well as the relevant atmospheric processes.

The required vegetation, soil and atmospheric properties will be retrieved from the hyper-spectral multi-angular radiometric data provided by SPECTRA by matching simulated TOA radiance to measurements. The values of the bio-geophysical variables

that best account for these observations are deemed to accurately represent the state of the environment.

The simplest (and least demanding in terms of computer resources) models in this category, for instance, assume that the geophysical medium with which light interacts is homogeneous in the horizontal plane.



**Figure 5.1:** Schematic of how bio-geophysical variables are retrieved by matching simulated to measured spectra; LIDF = Leaf Inclination Distribution Function; other variables described in the text (ESA 2001).

These one-dimensional vertical models may require typically five to seven variables to provide a realistic simulation of the measurements. If the medium is composed of several homogeneous media, the number of variables needed to simulate the measurements increases with the number of media in the scene. A wide choice of models is available in the literature: see for instance, Jacquemoud et al. (1995), Privette et al. (1996), and Gobron et al. (1997).

On the other hand, if the scene of interest is radiatively heterogeneous (in the sense that the different objects in the scene interact sufficiently strongly between themselves to affect the propagation of light throughout the scene), then the overall reflectance of that scene will not depend only on the properties of the individual elements, but also on their spatial distribution relative to each other and on complex radiative processes, such

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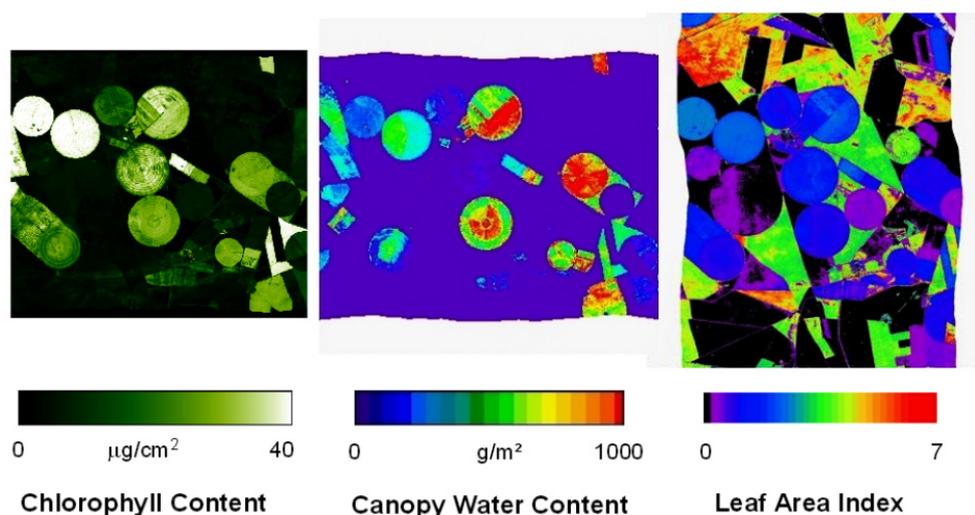
as multiple scattering. In this case, three-dimensional models may be needed to properly account for the measurements. They offer a much more stable theoretical basis and may generate much more accurate information, but at the cost of much larger sets of variables and extensive computer resources. Various three-dimensional models have been described in the literature, e.g. Govaerts and Verstraete (1998), Gastellu-Etchegorry et al. (2004), and Kimes et al. (2001).

### Algorithm Development

Various techniques have been designed to carry out model inversion against a data set (e.g. Verstraete and Pinty 2000):

- optimisation methods: designed to iteratively identify the best match between observations and model predictions
- Artificial Neural Networks (ANNs): algorithms that can be ‘trained’ to recognise patterns or estimate a value; and
- Look-Up Table (LUTs) approaches: based on the a priori simulation of a large number of situations, and the comparison of observations with the entries in this table to select the most probable solution.

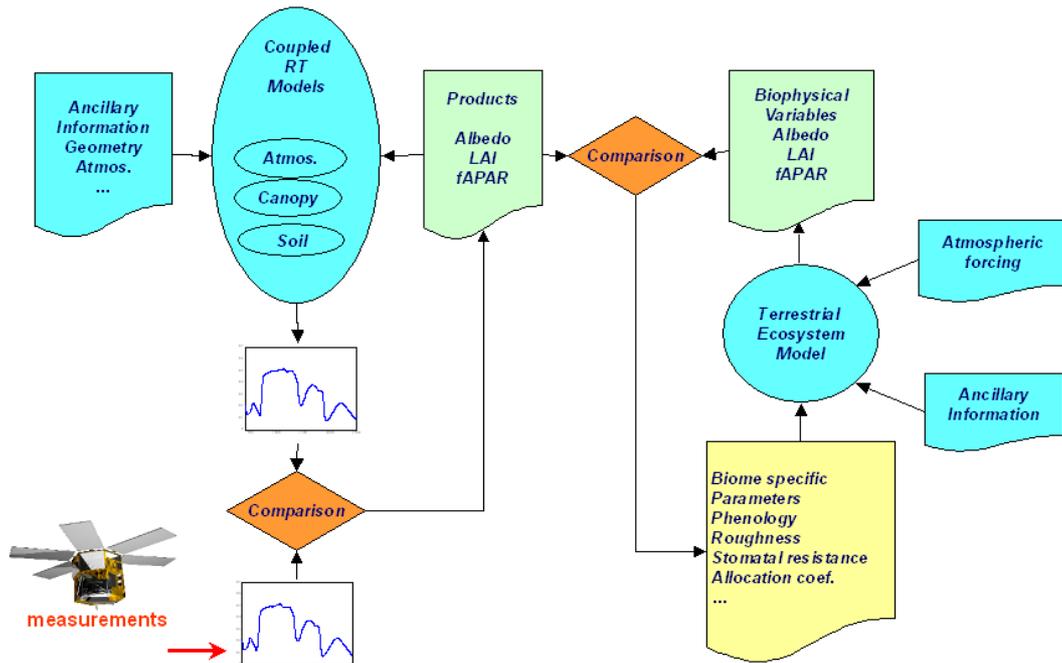
The spectro-directional radiometric data provided by SPECTRA will be processed as outlined above. Prototypes of such algorithms have been applied to data sets collected during preparatory campaigns. Spatial patterns of complex vegetation properties such as LAI, leaf chlorophyll and water content were derived in this way (Fig. 5.2).



**Figure 5.2:** Spatial patterns of leaf chlorophyll content, canopy water content and Leaf Area Index derived by inverse modelling of hyper-spectral multi-angular radiometric data over an agricultural site in Barrax (Spain) (Courtesy J. Moreno).

The end result of this process yields spatial and temporal fields of the (canopy) state variables, which can be ingested by higher level models of the biomes or climate.

### 5.3 From Canopy Variables to Model Parameters and Carbon Fluxes through Data Assimilation



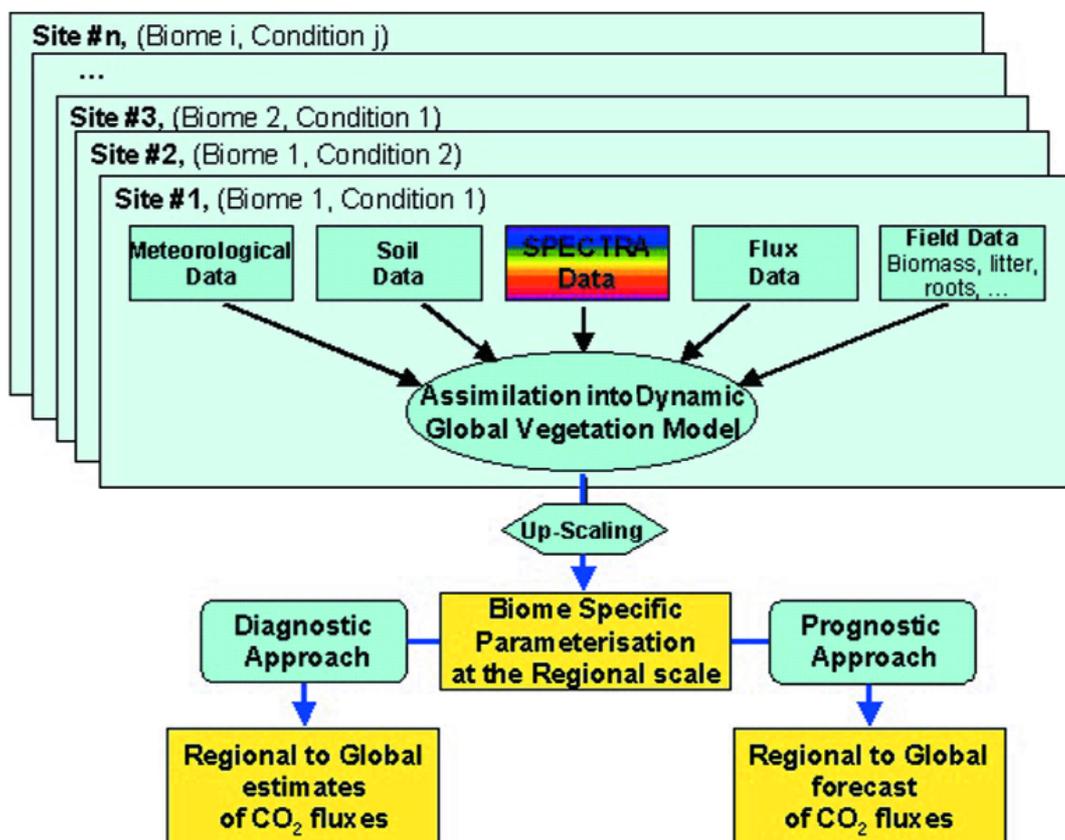
**Figure 5.3:** Conceptual scheme of data assimilation procedure to use observations of geo-biophysical variables provided by SPECTRA to constrain regional scale Terrestrial Ecosystem Models and estimate parameter values (Courtesy F. Baret).

Detailed models exist or will be constructed for each biome for which SPECTRA observations will be collected. The SPECTRA observations will be used to retrieve detailed maps of vegetation properties and for assimilation of these variables into coupled process- and radiative transfer models. A conceptual scheme of the data assimilation approach at the regional scale is shown in Figure 5.3.

Global models carrying the improved vegetation parameterisations are used to generate estimates of present carbon fluxes and stocks (Diagnostic mode) or predictions of the evolution of future carbon fluxes and stocks (Prognostic mode),

The bottom-up approach to describe the terrestrial carbon cycle directly simulates the processes involved in the exchange of carbon between the ecosystem and the atmosphere. The relevant scale is usually compatible with ground measurements used to calibrate and validate the models, as well as with the typical resolution of satellite sensors. The larger scale patterns are estimated by combining the fluxes corresponding

to individual land parcels. Figure 5.4 shows some of the important variables as well as the data flows involved in this approach. This bottom-up approach provides maps of flux estimates at the resolution of the input data. It allows direct use of satellite observations to characterize the dynamics and spatial variability of important state variables of the canopy and soil. Since it is based on a mechanistic description of the processes that control the fluxes, this approach can be used in a predictive way.



**Figure 5.4:** Conceptual scheme of SPECTRA data stream in the context of bottom-up modelling of terrestrial carbon fluxes (ESA 2001).

Diagnostic studies relate to current time, so additional information may be further used to improve accuracy of estimates. Global coverage observing systems such as MERIS, MODIS, MISR, ATSR, VEGETATION can be used to provide additional observations of vegetation at regional and global scales.



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## **6. Performance Estimation**

In the framework of the SPECTRA end-to-end simulator development, case studies were devoted to assessing the final contribution of the SPECTRA mission to the scientific goals outlined in Chapter 3. Attention was paid to the adequacy of the temporal and spatial coverage of the observations, the gain in accuracy of the variables retrieved, and the expected effect of this gain in large scale modelling applications.

### **6.1 Fulfilment of Temporal and Spatial Requirements**

Mission performance concerning temporal and spatial requirements was evaluated using a mission simulator originally designed to generate the optimal timeline of feasible acquisitions. The evaluation was performed as follows:

1. A set of 53 research sites was selected from the worldwide inventory developed in 1998 towards preparation of a Mission and Experiment Plan for a Land Mission (Jacobs and Menenti 2001). A schedule of requested data acquisitions was constructed using information provided by the scientists operating present sites. This schedule indicates monthly number and frequency of requested acquisitions for each site. In some cases, more precise dates were indicated in conjunction with planned Intensive Periods of Observations. The latter were based on the current mode of operation of the site and assumed to be representative of conditions at the time of mission operation. The ISCCP cloud climatology was used to estimate expected cloud cover on the date of each potential acquisition for any site.
2. Given the spatial distribution of sites, the schedule of requested acquisitions, swath width of the sensor and estimated cloud cover, the timeline of feasible and accepted acquisitions was generated.
3. ‘Customer satisfaction’ statistics, i.e. the number of successful over number of requested acquisitions, were acquired by simulating mission operation during an entire year.

The study confirms that the mission, as it stands today, is capable of meeting the observational requirements of a large community, depending on the spatial distribution of the sites, the timing of the required data and the cloud distribution. The current acquisition scenario of 53 sites uses less than 30%, on average, of the SPECTRA acquisition capacity for a week in the growing season. This implies that SPECTRA's capacity is far from exhausted by this scenario and has room to accommodate more sites. SPECTRA is flexible enough to change those sites at any time, which also allows the acquisition plan to be adjusted immediately for observations in the case of natural hazards or emergencies occurring (e.g. forest fires, volcano eruptions).

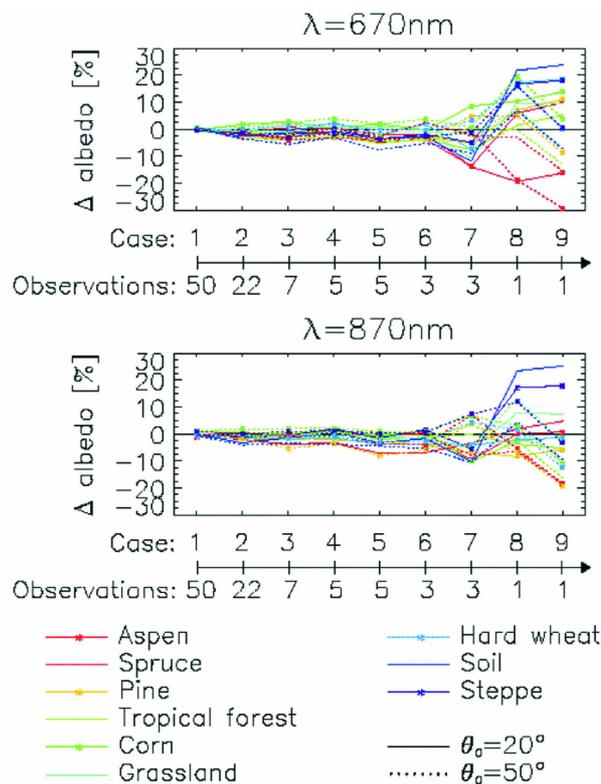
## 6.2 Assessment of Variable Retrieval Accuracy

### 6.2.1 Energy Balance Variables

#### Albedo (hemispherical reflectance)

Vogt et al. (2000) conducted a study to determine the qualitative and quantitative impact on the estimation of the hemispherical reflectance and the BRF field, of the following items:

- the number and position of angular observations
- the assumption of a Lambertian surface reflectance, and
- the error associated with the selection of a predefined BRF shape in the case of a single observation from an arbitrary angular position.



**Figure 6.1:** Relative error in albedo retrieval accuracy for various observation scenarios over several surface types for two solar positions (zenith angles of  $20^\circ$  and  $50^\circ$ ) in the RED (top) and NIR (bottom) spectral ranges. These results are based on an analysis of noisy data (Vogt et al. 2000).

Further studies (Pinty et al. 2000a, 2000b) confirmed that reliable albedo estimates can be derived from a limited number of angular measurements when they adequately

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sample the anisotropic reflectance field in angular space. A range of canopies was considered for which the whole BRDF was known. The three parameters of the so-called ‘Martonchik-modified Rahman-Pinty-Verstraete parametric model’ (MRPV; Engelsen et al. 1996) were adjusted on each surface type considering a variable number of viewing angles. The results showed that errors can be large when estimating hemispherical reflectance from a single angular measurement (Fig. 6.1). At least five, well-distributed angles are necessary to maintain errors within acceptable bounds. This is in good agreement with the actual SPECTRA angular specifications.

#### Separation of soil and foliage component temperatures

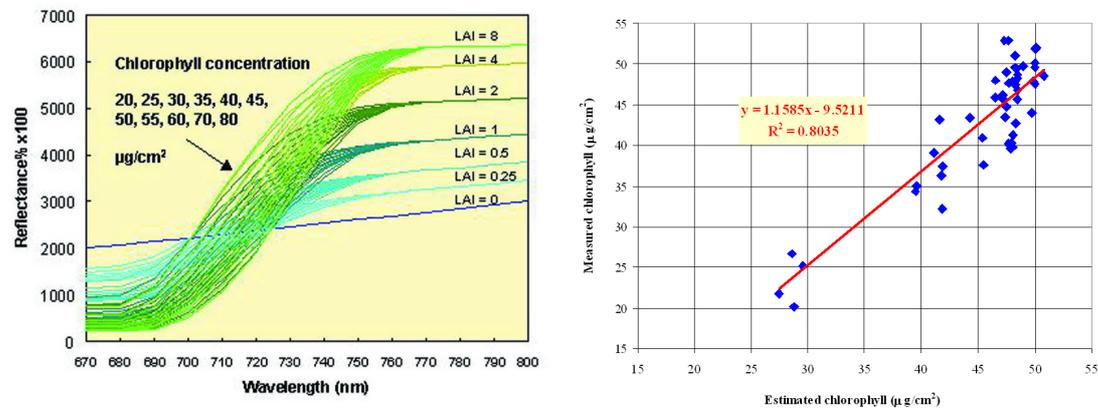
Because of the heterogeneity in the architecture of vegetation canopies, the energy balance varies significantly within the canopy space. The combination of thermal heterogeneity and canopy architecture determines a significant angular dependence of emitted radiance. Sobrino and Cuenca (1999) provided new insights into the anisotropy of the emissivity of leaves and soils. The anisotropy of emittance was exploited by Menenti et al. (2001a) and Jia et al. (2003) to estimate the component soil and foliage temperatures of different sites using the bi-angular TIR measurements obtained with ATSR-1 and ATSR-2. Accuracy of retrieval of soil and foliage temperatures was evaluated using field goniometric measurements of emittance (Jia 2004). The IMGRASS experiment gave a RMSE = 0.8 K for soil temperature and 1.5 K for foliage temperature. The GRSLSP experiment gave a RMSE = 1.4 K for soil temperature and 1.1 K for foliage temperature.

### **6.2.2 Biochemical and Canopy Structural Variables**

LAI has a long history of estimation from the measurements taken with low spatial and spectral resolution instruments, but these values have large error bars at both low (<1) and high values (>3). Recent research shows that LAI, fCover and canopy structure can only be decoupled using multi-angular measurements such as those provided by SPECTRA (e.g. Weiss et al. 2002).

Studies conducted as part of the preparation for the SPECTRA mission have shown that increasing the number of spectral bands and observational directions leads to more accurate estimates of canopy properties such as LAI, fCover and leaf chlorophyll content.

The retrieval problem was studied through simulations by Verhoef (2001), who evaluated the simultaneous retrieval of multiple variables by means of classical model inversion methods (Fig. 5.1). Canopy reflectance in the red edge was modelled (Fig. 6.2) for a series of combinations of LAI and leaf chlorophyll concentration. Eleven canopy variables were retrieved simultaneously, including soil brightness, canopy LAI, leaf chlorophyll concentration and aerosol single scattering albedo. These variables were retrieved using 14 bands evenly spaced in the spectral range between 670 and 800 nm.



**Figure 6.2:** Effects of LAI and chlorophyll content on canopy reflectance in the red edge spectral region (left) based on simulations for a given combination of chlorophyll content and LAI (after Verhoef 1998, 2001), Retrievals of leaf chlorophyll content (right) based such leaf-canopy models using CASI airborne imaging spectrometer data over corn crops are compared with data from field sampling (Haboudane et al. 2002)

Although generally smooth, it should be noted that each of these spectra corresponds to a unique combination of LAI and chlorophyll content. Thus, to accurately retrieve these variables from measurements of spectral reflectance, the latter must be sufficiently accurate and precise to identify which spectrum is actually being observed. Taking into account the additional ambiguities introduced by other variables affecting spectral reflectance, we may expect that measurements at higher spectral resolution and better radiometric accuracy will lead to smaller errors on retrieved variables.

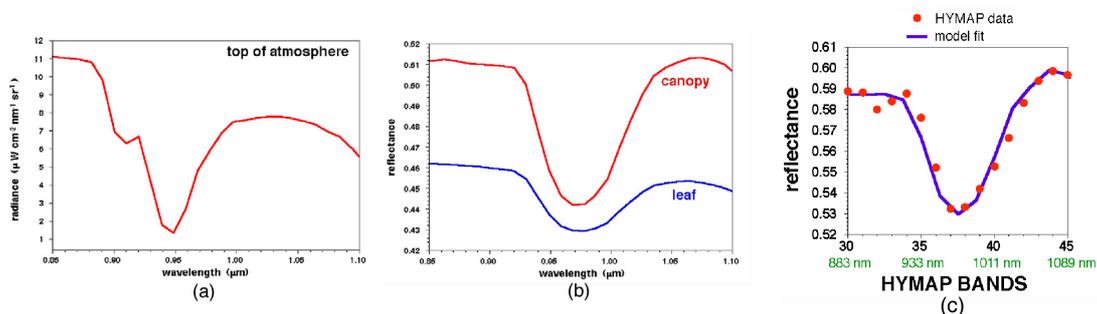
Although this approach requires further exploration to evaluate retrieval errors due to instrumental noise and other ambiguities, it suggests that measuring continuous reflectance spectra at high spectral resolution is necessary to constrain the inversion procedure and ensure the reliability of the results.

In a study (Haboudane et al. 2002) of the leaf chlorophyll content response to nitrogen fertilizer application practices on corn crops, a total of 64 experimental plots representing a wide range of nitrogen levels were over-flown with an airborne imaging spectrometer (CASI). Simulations that consisted of leaf and canopy reflectance modelling with PROSPECT and SAILH radiative transfer models allowed above-canopy reflectances, and indices based on carefully-defined narrow bands, to be used to produce estimates of leaf chlorophyll content. In Figure 6.2, chlorophyll content estimations are compared with leaf chlorophyll content measurements in the laboratory from plot field sampling showing a coefficient of determination  $r^2 = 0.804$  with a corresponding root mean square error  $\text{RMSE} = 4.35 \mu\text{g}/\text{cm}^2$ , or about 10% of mean chlorophyll content. For extension of this work to a broad range of crop types with different canopy architecture and background soil reflectances, the forward modelling

up-scaling methodology used here will need to be replaced with a general multiple variable inversion approach, as described in the previous references (e.g. Verhoef et al 2001, Weiss et al. 2002) in order for the retrieval accuracies to be preserved.

Using field data, the accuracy of retrieving LAI, leaf chlorophyll content, canopy structure and fAPAR was evaluated for eighteen situations, corresponding to six development stages and variations in leaf chlorophyll content and soil type. In this study, nine spectral bands each of 10 nm width were considered, centred at 500, 562, 630, 692, 710, 740, 795, 845, and 882 nm. Results (Weiss et al. 2000) showed that, for all four variables considered, the absolute RMSE decreased with the number of spectral bands, at least up to a certain number of bands. The bands were not selected in the same order, however, and the total number of bands needed to retrieve all four variables with the smallest possible error was eight out of nine in the limited spectral region. This results in the need to sample the spectral interval of relevance in a contiguous fashion.

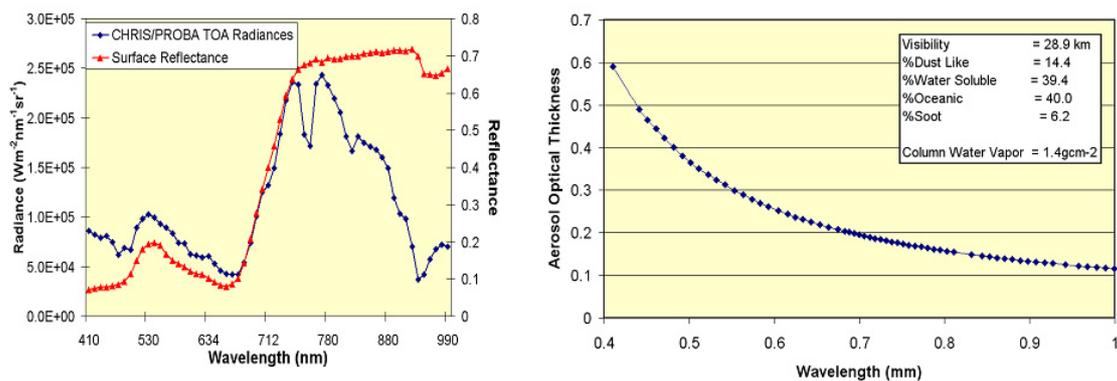
Leaf water content can be retrieved by analysing specific spectral absorption bands of liquid water in the Short-Wave InfraRed (SWIR). If a high enough spectral resolution is available, the depth of the absorption bands can be directly measured (even for several absorption features across the spectral range). With a good spectral resolution and spectral stability, the shape of the absorption bands can be fitted to the expected theoretical behaviour of bound liquid water. Water content can then be retrieved with a high accuracy, but most importantly with a high stability and robustness. An evaluation of this approach was presented by Moreno (2001). A coupled soil, leaf/canopy, atmospheric model (Fig. 5.1) was directly inverted against continuous reflectance spectra at high spectral resolution. This approach was evaluated using AVIRIS, DAIS and HYMAP data sets collected in Barrax, Spain at different times. Simulated reflectance spectra (Fig. 6.3) were evaluated against HYMAP data at different locations. Although spectral matching was very good overall, the deviations that were observed at some wavelengths clearly illustrate the importance of using continuous reflectance spectra at high spectral resolution for accurate water content retrieval.



**Figure 6.3:** (a) The separation of water vapour absorption effects in top of atmosphere radiances from liquid water effects at the canopy and at the leaf level (b) requires precise modelling of the spectral reflectance curve; (c) fitting of precise spectral models to actual spectrometer data (HYMAP) allows one to retrieve information about vegetation properties (leaf water content) (Courtesy J. Moreno).

### 6.2.3 Retrieval of Atmospheric Information

The effects of atmospheric aerosols remain a major source of uncertainty in the interpretation of radiometric data observed from space to determine land surface properties. Experience with atmospheric corrections of airborne sensors, in particular of AVIRIS (flying in the ER-2 high altitude aircraft) and multiangular data, such as MISR, has shown that the intrinsic atmospheric information contained in the data can be used to account for atmospheric effects, describing aerosol effects and variations in column water vapour amounts on a pixel-by-pixel basis (Gao and Goetz 1990, Gao et al. 1993, Moreno and Green 1996). The recent availability of hyper-spectral, multiangular data from the spaceborne CHRIS instrument, onboard the ESA technology mission PROBA, has demonstrated (Guanter et al. 2003) the capability for accurate atmospheric correction of multiangular data with high spectral resolution (Fig. 6.4).



**Figure 6.4:** Correction of hyper-spectral, multi-angular CHRIS/PROBA data for atmospheric effects without ancillary information; Barrax, Spain, 12 July 2003: (left) Top-of-atmosphere radiance and derived surface reflectance versus wavelength; (right) aerosol optical thickness retrieved by inverting the TOA radiometric data provided by CHRIS/PROBA (Courtesy J. Moreno).

### 6.2.4 Summary

The laboratory, field, and airborne evidence collected over the past decade jointly point to the significant advantages of acquiring spectral data at high resolution, over those parts of the spectrum where specific features can be exploited (see Table 6.1 for a summary overview). Examples include the so-called ‘red-edge’ exhibited by vegetation canopies around 650-750 nm, and the distinction of leaf and canopy liquid water from water vapour absorption bands in the middle infrared.

Variable	Sampling of angular and spectral dimensions		
	1 view angle, 2 bands	Multiangular, hyperspectral	
		Synthetic data	Actual data
Fractional cover	40%	5%	
fAPAR	30%	5%	
Albedo	30%	2%	8% (Jacob et al. 2002)
LAI	125%	10%	20% (Weiss et al 2002)
Leaf chlorophyll	85%	10%	10% (Haboudane et al. 2002)
Leaf water	Not feasible	20%	15% (Fernandez and Moreno 2003)
Leaf dry matter	Not feasible	20%	
Foliage temperature	Not feasible	1 K (mixed target)	1.3 K (Jia 2004)
Soil temperature	Not feasible	2 K (mixed target)	1.1 K (Jia 2004)
Fraction living / dead	Not feasible	20%	

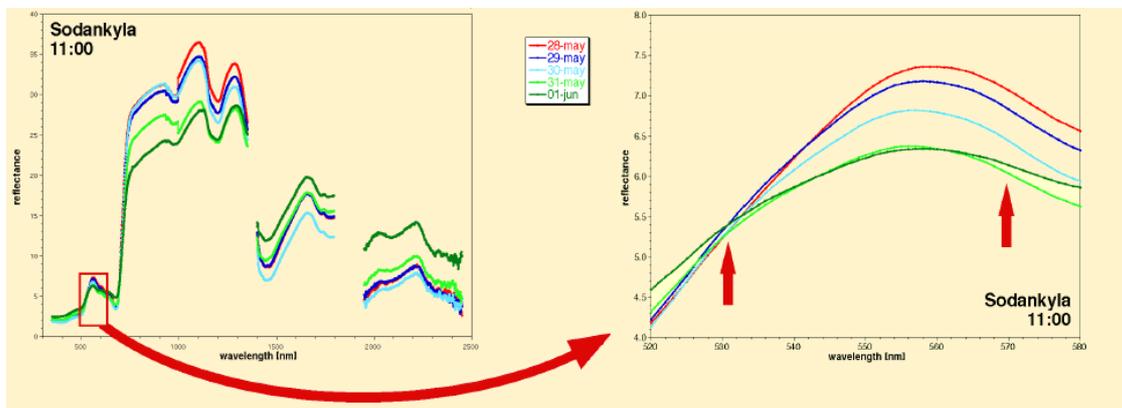
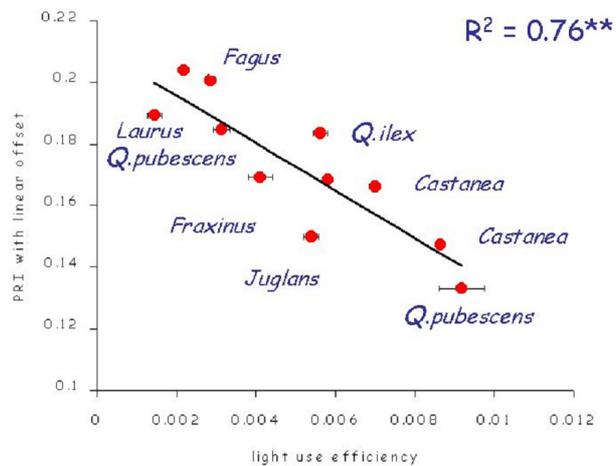
**Table 6.1:** Retrieval error for key properties of terrestrial vegetation; based on results of direct/inverse radiative transfer modelling and the inversion of actual data; ‘not feasible’ here means ‘not feasible with sufficient accuracy to be useful’ (Table updated from ESA 2001).

A high spectral resolution and data acquisitions at multiple angles of observation have both been shown to improve the quality and reliability of the retrievals very significantly. New algorithms in this respect have been developed, tested and applied operationally to POLDER and MISR data, and the SPECTRA mission will thus be able to capitalize on these advances, as well as to contribute new approaches.

### 6.3 From Canopy Variables to Model Parameters and Carbon Fluxes

#### 6.3.1 Spectral Radiometric Data and Biome Specific Parameters: The Photochemical Reflectance Index and the Light Use Efficiency

Experimental research on vegetation response to climate has shown that spectral reflectance of vegetation canopies is closely related to biome properties (Figs. 4.2 and 6.2), such as the ones used to parameterise the response of vegetation to climate. Raddi et al. (2001) showed that the Light Use Efficiency (LUE) of different species (Fig. 6.5) is closely related to the Photochemical Reflectance Index (PRI), where  $PRI = (\rho_{570} - \rho_{531}) / (\rho_{570} + \rho_{531})$ . The PRI can be determined from spectral radiometric data as demonstrated by the experiments carried out at the Sodankylä boreal forest site (Davidson et al., 2003). These results indicate that hyper-spectral radiometric data contain information on biome parameters such as LUE.



**Figure 6.5:** (top) Linear relationship between PRI (corrected for red-blue baseline reflectance) and light use efficiency ( $e$ ) at the leaf level for several broadleaved forest species (Raddi et al. 2001); (bottom) PRI observations with high spectral resolution Top Of Canopy radiance measurements at a boreal forest site (Sodankylä, Finland) (Courtesy J. Moreno).

### 6.3.2 Assimilation of Soil and Foliage Component Temperatures to Improve Parameterisation of Land – Atmosphere Exchange of Heat

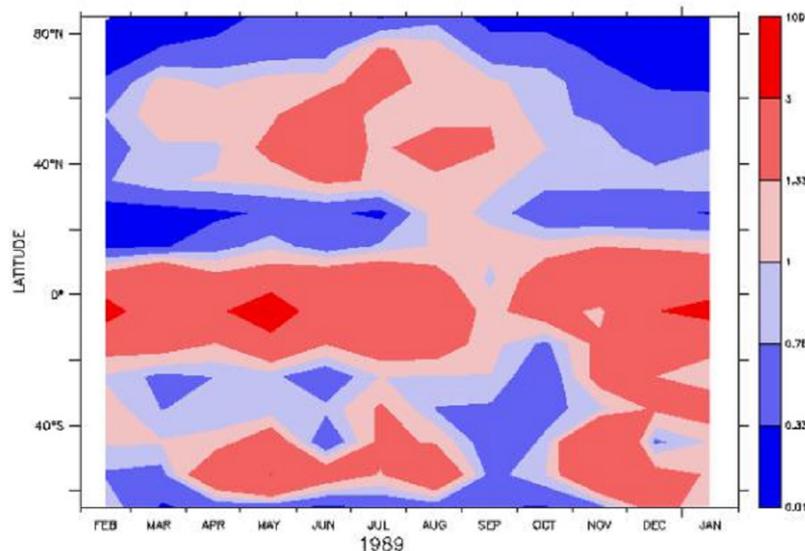
Van den Hurk et al. (2002) assimilated observed time series of foliage and soil temperature, obtained with the dual view thermal infrared measurements provided by ATSR-2, to estimate the roughness length for sensible heat transport. This model parameter – which determines the allocation of net radiation into latent and sensible heat flux – cannot be determined directly from experiments at the scale of a model grid. Data assimilation was performed for two regions near Barrax, Spain and Cabauw, The Netherlands, and throughout one growing season. This provided maps of roughness length for sensible heat transport at different times through the year. Differences between the optimal roughness values thus obtained for Spain and The Netherlands were qualitatively consistent with expectations: smaller thermal roughness lengths

were found in the Spanish region, where sparse canopies were the dominant vegetation type. Forecasts of air temperature and humidity were shown to be slightly improved.

### 6.3.3 Impact of the Ingestion of Leaf Area Index Observations on Global Land Evaporation

Terrestrial vegetation controls the exchange of water between land and the atmosphere. Parameterisations of this process have been implemented in most state-of-the-art models used for Numerical Weather Prediction (NWP) and Climate Simulation (e.g. Koster and Suarez 1992, Dickinson et al. 1995, Noilhan and Mahfouf 1996). In these implementations, LAI values (either constant in time or with a seasonal variation) were assigned to broad vegetation classes by means of a look-up table, and spatial distributions of these vegetation types were specified from climatologies as from Wilson and Henderson-Sellers (1985) or Olson and Allison (1983). However, the interpretation of the vegetation types and associated parameter assignment (parameterisation) may vary widely across modelling systems, and usually does not allow inter-annual variability of vegetation conditions to be incorporated.

The case study described by Van den Hurk et al. (2003) demonstrated the significant impact of accuracy of LAI observations on global land evaporation. Estimates of monthly LAI were obtained from the ISLSCP Initiative III database and matched with each land cover type used by the global ECMWF NWP model. The global ECMWF NWP treats LAI as a biome specific parameter, i.e. as an entry in the table of the values by biome of the parameters used in the Land Surface Scheme. The monthly LAI values and the estimated random error were ingested through modified forms of this table.



**Figure 6.6:** Hovmüller-diagram of zonal means of the ratio  $\sigma^2_{NLAI}/\sigma^2_{SLAI}$  as a function of time of year. Reddish to red colours indicate that the impact on land evaporation due to LAI noise is larger than the impact of atmospheric noise (van den Hurk et al. 2003).

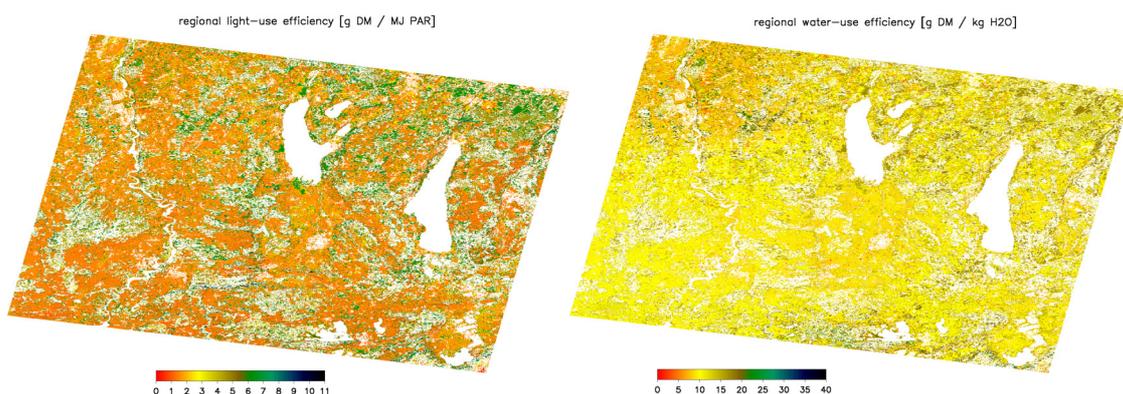
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The results indicate that in areas and periods where land surface evaporation is significant, variability in the leaf area index can clearly be discerned from variability induced by noise due to inaccuracy of initial atmospheric conditions: around the equator in all seasons, and over mid latitudes in the Northern Hemisphere in the summer season. The results indicate that the representation of LAI in the current ECMWF model does have a clear influence on the evaporation (Fig. 6.6).

The study shows that the accuracy of the LAI values prescribed for the terrestrial biomes has a detectable impact on the forecast accuracy of a global NWP model. Observations of Leaf Area Index can be obtained from the radiometric measurements provided by SPECTRA. The mission can then provide those observations necessary to characterize in detail the spatial and temporal variability of LAI for all biomes sampled by the SPECTRA mission.

#### 6.3.4 Use of Regional-Scale Water and Light Use Efficiency Parameters in Global Models of Terrestrial Carbon Fluxes

An ongoing scientific support study (Menenti et al. 2004) aims to provide proof-of-concept for a procedure to generate global carbon fluxes using a chain of simulated SPECTRA image data and numerical experiments at the regional and global scale. In the framework of this study, two process parameters have been selected, namely Light Use Efficiency (LUE) and Water-Use Efficiency (WUE). LUE (defined as the ratio of NPP to absorbed photosynthetically active radiation) and WUE (NPP divided by plant evapotranspiration) regulate the carbon uptake efficiency for given amounts of available radiation and water, respectively. Net primary productivity (NPP) is a measure of vegetation activity and carbon cycling (Olson et al. 2001).



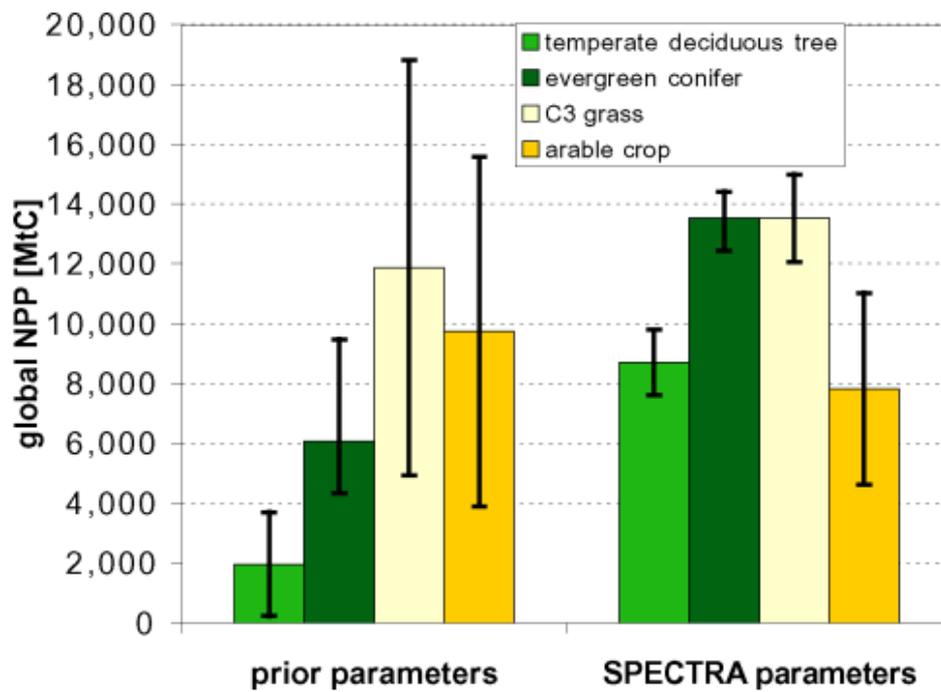
**Figure 6.7:** Regional scale maps of mean annual biome specific parameters in the Alpine foreland site for the period November 1999 to October 2000: (left) light use efficiency [grams of dry matter per MegaJoule photosynthetically active radiation]; (right) water use efficiency [grams of dry matter per kilogram of transpired water] (Courtesy of M. Probeck).

High-resolution simulated SPECTRA-like data were generated using a chain of models (GeoSail and MODTRAN). A basic data assimilation was performed using the ecosystem model PROMET to estimate values of LUE and WUE specific for the Plant Functional Types (PFTs) present in a selected 50 km x 50 km scene. The Biosphere Energy Transfer Hydrology Scheme (BETHY) (Knorr 2000) has been adapted to compute sensitivities to changes in LUE and WUE. Values of LUE by PFT were assigned based on Ruimy and Dedieu (1994), while the water-stress dependence was parameterised using studies by Beerling and Quick (1995) for C3 plants, and Kim and Verma (1991) for C4 vegetation. Through this procedure, a new set of LUE and WUE values and variabilities (Fig. 5.7) were determined for the selected biome, which substitutes the parameter values currently used in BETHY (see Table 5.2). For the standard, prior parameters of BETHY, we assume 75% uncertainty for LUE, and 50% for WUE, with covariance set to zero. For the parameters based on the regional assimilation of SPECTRA-like data, we use the in-scene variability to approximate the error covariance matrix of the BETHY parameters.

		Literature		SPECTRA	
		Mean	Uncertainty	Mean	Uncertainty
Temp. dec. tree	LUE	1.01	75%	6.15	12%
	WUE	10.17	50%	16.37	25%
Evergreen conifer	LUE	1.57	75%	4.38	9%
	WUE	13.73	50%	12.28	7%
C3 grass	LUE	1.26	75%	1.49	11%
	WUE	6.96	50%	9.48	13%
Arable crop	LUE	2.71	75%	1.96	34%
	WUE	8.43	50%	10.60	40%

**Table 6.2:** Parameters and their uncertainties as (a) from literature values (Ruimy et al. 1994; Beerling and Quick 1995); (b) retrieved from SPECTRA-like data.

A total of ten runs were carried out to approximate the sensitivity of the NPP simulated by BETHY to changes in PFT-specific LUE and WUE (Kaminski et al. 2003): (a) control run with PFT specific LUE and WUE values as specified from the literature; (b) two runs with LUE changed to 110% and 90% of the control run's LUE, respectively; (c) two runs with modified values of the water stress parameter in the stomatal conductance model, affecting WUE. These five runs were then repeated using the mean values of LUE from the regional assimilation. Based on this extensive sensitivity study, approximate means and uncertainties were computed for the global integrals of NPP for the four plant functional types present in the regional assimilation scene. Global values of NPP for the four PFTs of the study are shown in Figure 6.8, complete with error bars.



**Figure 6.8:** Estimates of global NPP with the BETHY biosphere model for four plant functional types, with error bars. Left: Using literature values for BETHY parameters LUE and WUE. Right: BETHY parameters WUE and LUE taken from the regional assimilation of SPECTRA-like data (Courtesy of W. Knorr).

There is considerable impact on the estimated mean NPP in all cases, accompanied by a large reduction in the NPP uncertainty. Even though this is only a first demonstration, it illustrates the impact SPECTRA data can have on global-scale simulations of biosphere–atmosphere carbon fluxes.

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## 7. User Community Readiness

The land surface processes and terrestrial carbon communities have a long experience in using hyperspectral and multidirectional data, thanks to the major contributions made possible, for instance, by the AVIRIS and the MISR missions. ESA's CHRIS/PROBA technology demonstration project also uses an observational approach similar to that of SPECTRA, and these products have been exploited by an active community of users. A wide range of scientific communities (e.g. climate simulation, Earth system modelling, agricultural meteorology and modelling, functional ecology, biogeochemical cycles, biogeography) thus has already acquired significant experience with hyperspectral and multiangular measurements and will be ready to take full advantage of the SPECTRA mission when it becomes operational. SPECTRA products will be used to enhance research coordinated by international programmes such as IGBP (International Geosphere-Biosphere Programme), WCRP (World Climate Research Programme), IHDP (International Human Dimensions Programme on Global Environmental Change) and DIVERSITAS who share the common challenge to develop and apply a range of Earth system models including physical climate, ecological and human systems. An example of an integrated project of all four programmes is the Global Carbon Project (GCP), which aims to combine models and observations to yield a complete picture of the global carbon cycle. A broader goal that includes all biogeochemical cycles and ecological processes is pursued by the Global Analysis, Integration, and Modelling (GAIM) framework activity of IGBP. These research activities need to rely on high-quality observing systems covering a range of scales from field to global.

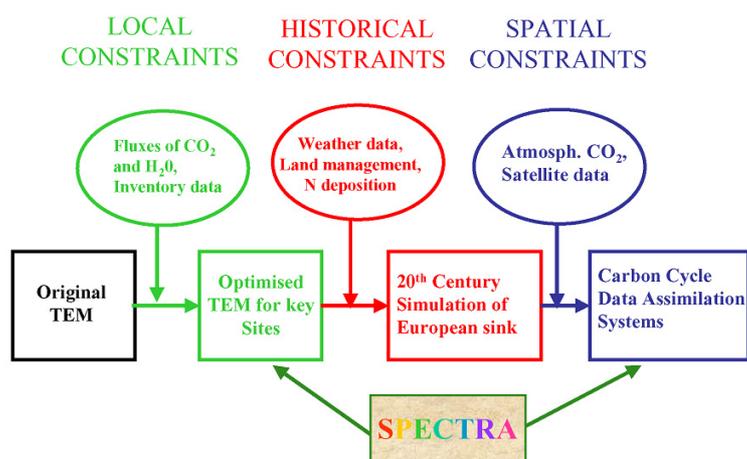
Currently, all global biosphere models are based on a combination of land cover maps that recognise a finite number of plant functional types, each characterized by a finite number of parameters that are constant throughout the globe and during the year. As shown in the previous chapter, the SPECTRA mission will provide better estimates of these parameters, as well as the associated statistics, at the appropriate times for the various locations.

SPECTRA products will prove useful for a broad family of global biosphere models and scientific users. The Earth system modelling community will take advantage of SPECTRA products in three different ways. Firstly, these products can serve as a direct input for the parameterisation of ecological models (see Table 7.1). Secondly, SPECTRA products may be used for model validation in cases where the same quantities can be simulated independently by the models. Thirdly, models that form part of a data assimilation system can use SPECTRA products as observational constraints to optimise internal model parameters and initial conditions.

Application	Model System	Operating Institute
Ecological	SORTIE	Princeton University
	FORSKA	PIK
Ecological-hydrological	Medrush	University of Sheffield
Ecological-biogeochemical	ORCHIDEE	LSCE/LMD
	CABLE	CSIRO-DAR
	CENTURY	NCAR
	LPJ	Lund University/PI:/MPI-Jena
	CASA	Carnegie Institution, Stanford University
Coupled vegetation-climate models	TRIFFID/MOSES	Hadley Centre
	CCSM	NCAR
	GENESIS/IBIS	University of Wisconsin
	SiB/CSU-GCM	Colorado State University
	CGC3M network	Canadian Climate Centre
	BETHY/ECHAM	MPI-Jena/Hamburg

**Table 7.1:** Modelling systems with the capability of using of SPECTRA observations.

Examples are the Carbon Data Assimilation System (C-DAS) co-ordinated by NCAR, the data/model synthesis programme of SCEOS/University of Sheffield, the CarboEurope FP5 project CAMELS co-ordinated by the Hadley Centre, and the Carbon Cycle Data Assimilation System (CCDAS) operated by MPI Jena, MPI Hamburg, CSIRO-DAR, and FastOpt, Hamburg (Fig. 7.1).



**Figure 7.1:** The possible use of SPECTRA data within the CarboEurope project CAMELS. Several terrestrial ecosystem models (TEM) are constrained in consecutive steps. SPECTRA data can be used for better TEM parameterisations, as well as in the final data assimilation step (Courtesy W. Knorr).

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Research into the functioning of ecosystems, such as measurements of CO<sub>2</sub> and water exchanges with eddy covariance towers, uses remote sensing derived biophysical data products of the surrounding landscape in order to extrapolate local results to larger scales (e.g. Ameriflux, CARBOEUROFLUX, CAMELS, TCOS-Siberia, SIBERIA II, CARBOEUROPE IP, LBA). Other large-scale ecosystem research programmes, such as the LTER long-term research programme and the experimental investigation of the University of Alaska/Fairbanks, already use remote sensing information for the upscaling of hydrological and biogeochemical models to watersheds and other regional scales. This community will benefit from SPECTRA products providing information with much improved resolution and for considerably more biophysical parameters than possible with current instruments.



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## **8. The Global Context**

This chapter addresses the role of SPECTRA for climatic and environmental issues that are likely to be at the top of the agenda by the end of this decade, in the overall context of Earth Observation, international treaties and conventions, and GMES (Global Monitoring for Environment and Security). It also gives an indication of who the main beneficiaries and users will be.

### **8.1 The Scientific Context for the SPECTRA Mission**

The SPECTRA mission will make significant contributions to the development of Earth System Science, because it will provide unique data to characterise vegetation properties on a global scale, through a detailed observation of most significant biomes. Parameterisations of biosphere processes will take on increasingly critical importance, and their accuracy and reliability will need to improve to match these expectations.

SPECTRA fits into an overall strategy where all pieces of data must be used together to understand the complex terrestrial vegetation processes related to the carbon cycle. Networks of atmospheric CO<sub>2</sub> measurement towers, surface measurements, and complementary satellite information (atmospheric CO<sub>2</sub> columns, atmospheric dynamics, global surface maps) are elements that must be combined in modelling to achieve optimal exploitation of SPECTRA data. In this context, the SPECTRA mission objective fits very well within the existing international research programs (e.g. IGBP, WCRP, GCP).

In 1984 the land science community initiated the International Satellite Land-Surface Climatology Project (ISLSCP) to advance understanding of biosphere-atmosphere interactions through a combination of regional scale experiments and quantitative analyses of radiometric data from space. This community has matured and grown over the last twenty years, developing a range of international research programmes (see Chapter 7) following the same scientific strategy. SPECTRA contributes to this strategy with a coherent observational programme from space and a network of dedicated research terrestrial sites.

### **8.2 The Complementary Nature of SPECTRA in an Earth Observation Context**

Operational global Earth Observation missions at medium resolution (e.g. between 250 m and 1 km) can be assumed to operate throughout the next ten years, because of their confirmed usefulness and widespread exploitation for a whole range of practical applications, from weather and climate forecasting to agriculture, and from environmental monitoring to natural hazard and early warning surveillance systems. At the same time, the current interest in very high spatial resolution sensors (of the order of one metre or even less) is likely to continue, to sustain specific applications such as urban planning, mapping, and general surveillance. SPECTRA will thus fill an important gap in

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this observation strategy, by providing very detailed spectral and directional measurements at a spatial resolution high enough to be directly related to in-situ measurements acquired simultaneously through field campaigns, and over regions large enough to characterise the environment over the typical grid cell of global models. SPECTRA observations will prove useful in investigating local to regional scaling issues, and for fully exploiting the medium resolution instruments that offer daily global coverage.

The SPECTRA mission will also be a very useful complement to global missions by providing validation of the biophysical products derived from large-swath satellites and improvements in the exploitation of global observations by low-resolution satellites.

### **8.3 SPECTRA in the Context of International Environmental Conventions and Treaties**

#### **SPECTRA and GMES**

The Global Monitoring for Environment and Security (GMES) is a joint ESA-EC initiative to improve the monitoring of European and global environments and to promote the sustainable development and management of natural resources, as well as improving the security of Europe's citizens. SPECTRA will contribute directly to the GMES initiative and help take full advantage of other missions by providing detailed information over specifically selected sites to address GMES issues. SPECTRA will contribute directly to the R&D component of GMES and help define new and better methods for exploiting remote sensing data in the generation of reliable and accurate environmental information.

#### **SPECTRA and the International Environmental Conventions and Treaties**

Negotiations of inter-governmental treaties and conventions (e.g. the Kyoto Protocol, the Ramsar Convention on Wetlands, the Convention to Combat Desertification), as well as action plans to deal with these issues, must be based on reliable, accurate environmental information. The SPECTRA mission will contribute significantly in this area, and will also allow the assessment of ecosystem degradation or recovery on a regional scale.

SPECTRA is especially relevant in the context of conventions that explicitly use the concept of monitoring a 'network of sites'. This is the case for the 'Ramsar Convention on Wetlands' (<http://www.ramsar.org/>). Selecting a representative number of wetland sites within the set of SPECTRA sites will significantly enhance the observation capabilities in the Ramsar context, because it will provide a unique type of data, at proper spatial and temporal resolutions to complement other detailed in-situ observations. The current ESA Globwetland project uses 50 sites in 21 countries worldwide, but relies on MERIS data for inland water characterisation, something that could be greatly improved with SPECTRA data. Similarly, the UN Convention to

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Combat Desertification (UNCCD) is also based on the monitoring of a network of instrumented sites, in addition to regional and global observation by satellite-borne sensors. SPECTRA data is particularly suited for monitoring desertification-threatened areas because it has the appropriate spatial resolution and the crucial radiometric and spectral resolution to detect the small changes in vegetation (dry vegetation in most cases) over soil backgrounds (potentially an indicator of soil erosion) through observable changes in soil composition.

It would be extremely useful for SPECTRA to be operational in or shortly after 2008, because that year marks the start of the initial commitment period for the Kyoto Protocol (KP) to the United Nations Framework Convention on Climate Change (UNFCCC). In particular, in relation to policies to mitigate carbon emissions, it has to be verified whether the intended land use changes are having the expected impact on terrestrial carbon uptake.



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## 9. Application Potential

The primary users of the SPECTRA observations, as well as the applications that are driving the mission requirements, have been amply described in previous chapters. At the same time, it is widely recognized that hyperspectral multidirectional measurements at relatively high spatial resolution will also be of great use in many other fields.

Spectro-directional imagery is increasingly seen as an acquisition technology that enables geobiophysical variables of the Earth's surface to be mapped with unprecedented accuracy. It is expected that direct application of SPECTRA will be of most interest for natural rather than managed ecosystems. However, its spectro-directional capability with good re-visit capability will advance monitoring of both.

The SPECTRA mission will contribute to further advances in remote sensing by helping to:

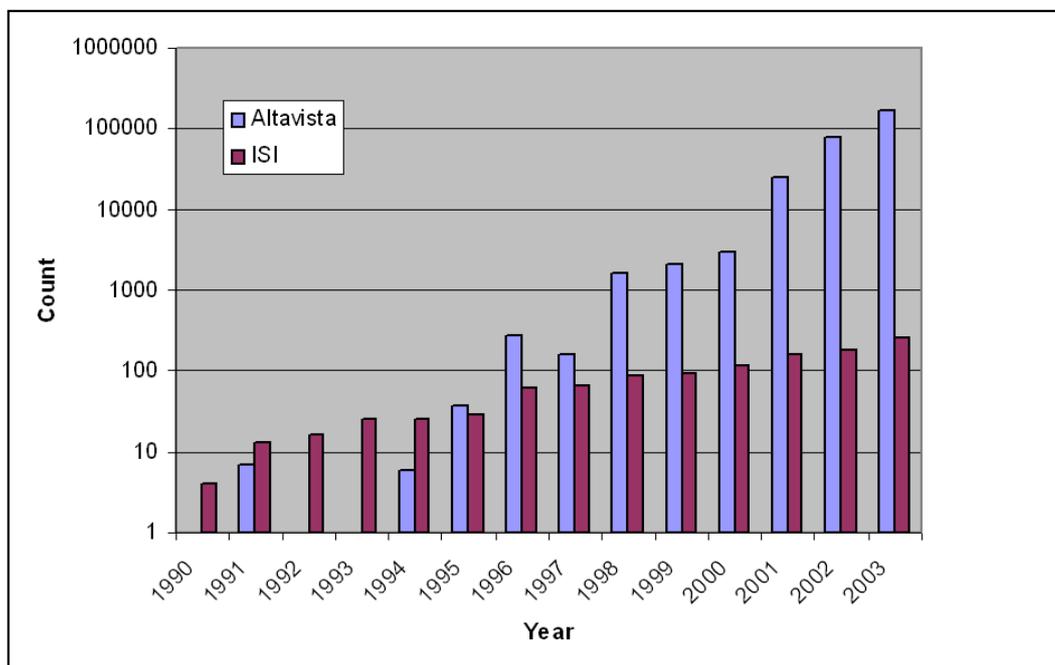
- design new or better algorithms for the exploitation of current and future sensors
- define more appropriate observational requirements for the sensors that will be needed in the subsequent decade (2011 to 2020)
- re-analyze measurements obtained in the past with less sophisticated sensors.

Directional imaging spectroscopy and thermal acquisition have already supported or been used for the applications listed below, and the corresponding variables have been directly or indirectly quantified using inversion, assimilation, spectral unmixing, and/or correlation techniques (Green et al. 1998, Schaepman et al. 2001, Verhoef & Bach 2003, Weiss et al. 2000, Pinty et al. 2001, Strub et al. 2003).

### New emerging applications

The particular success of hyperspectral and multi-angular retrievals is based on improved data quality (more mature technology, better calibration stability, increased number of spectral bands and observation angles, high signal-to-noise-ratio), wider availability of consistent observations to the user community (c.f. GMES initiative), and emerging new applications. Figure 9.1 underlines the exponential growth of this potential.

A major area of innovation is monitoring of agricultural areas to maximize yield through adaptive farm management and use of comprehensive observations of soil and crop conditions. Modelling of cropland functioning for agricultural research and forecasting already uses hyperspectral data from aircraft remote sensing and may then benefit from the availability of SPECTRA products.



**Figure 9.1:** References on websites using imaging spectroscopy for their application between 1990 and 2003. Counts (in logarithmic scaling) are based on ISI Web of Science entries using peer reviewed journals only and total hits in Altavista (Courtesy M. Schaepman).

Examples of the potential benefits being explored by agricultural researchers include: the potential of leaf chlorophyll content to serve as a measure of the crop response to nitrogen application (Haboudane et al. 2002), the potential of hyperspectral data and local micrometeorological data to improve the sustainability of nitrogen management in crops (Pattey et al. 2001), and the use of remote sensing input data in crop growth models to improve productivity estimates (Bach and Mauser 2003). SPECTRA will provide hyperspectral data, with which to explore the potential of and develop the first methodologies for large agricultural units. Applications will eventually require spatial resolutions well below 50 m. With more repetitive observations covering far more sites globally compared to airborne techniques, SPECTRA products will help to bridge an important gap between agricultural research and the description of managed ecosystems in Earth system models. There is also growing interest in the study of CO<sub>2</sub> and other greenhouse gas fluxes from agricultural and pasture lands within the biogeochemical research community (e.g. CarboEurope Greengrass project).

The emerging applications noted below reflect recent findings in spectro-directional research, and references are given for each to underline the application potential:

- Vegetation stress detection, and determination of invasive species for ecological monitoring in forestry and agriculture (Clevers 1999, Okin et al. 2001, Rahman et al. 2003, Sims and Gamon 2002, Underwood et al. 2003, Zarco-Tejada et al. 2002).

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- Monitoring of degradation of arid and semiarid ecosystems (Asner and Heidebrecht 2003, Huete et al. 2003, Leone and Sommer 2000).
  - Nitrogen mapping for agricultural crops (Ogunjemiyo et al. 2002, Pattey et al. 2001).
  - Fuel Moisture Content (FMC) mapping for forest fire mitigation and spread models (Koetz et al. 2004, Riano et al. 2002).
  - Assessment of mineral composition and soil crust formation to estimate infiltration rate, soil runoff, and erosion (Ben-Dor et al. 2003, Kruse et al. 2003).
  - Mapping inland and coastal zones water quality (Brando and Dekker 2003, Chang et al. 2003, Galvao et al. 2003).
  - Assessment of algae contaminated snow for water supply management (Painter et al. 2003).
  - Retrieval of aerosol optical properties affecting the Earth's climate and water supply (Kaufman et al. 2002, King et al. 2003).
  - Calibration, validation and simulation of instruments and data for performance estimation (Green et al. 2003, Kneubuehler et al. 2003, Verhoef and Bach 2003)
  - The surface target diagnostic power of hyperspectral/multiangular observations is expected to have increasing value in the context of applications related to security issues and dual use.

It is important to stress that SPECTRA will offer a whole new range of measurements with a combination of unprecedented spatial, spectral and directional characteristics. Even though a number of specific applications have been or can be anticipated, past experience with ESA's ERS and Envisat programmes has demonstrated that new ideas arise and previously unforeseen applications are developed when high quality data become available to the scientific and user communities.

With the current scenario of planned Earth Observation missions, and after recent decisions on the characteristics of future Landsat class satellites, no capability is foreseen to acquire high resolution TIR data. There is, however, well documented interest in such data for water management applications. SPECTRA might well be the only source of such data for years to come. It thus contributes directly to the R&D component of the ESA-EC GMES initiative and is also expected to lead to significant improvements in the efficiency of the tools and techniques applicable to other operational sensors.



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## Acronyms and Abbreviations

AATSR	Advanced Along Track Scanning Radiometer
AEROCARB	Airborne European Regional Observations of the Carbon Balance
AirMISR	Airborne Multi-angle Imaging Spectrometer
ANN	Artificial Neural Network
ATSR	Along Track Scanning Radiometer
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
BETHY	Biosphere Energy Transfer HYdrology Scheme
BOA	Bottom of Atmosphere
BRDF	Bi-directional Reflectance Distribution Function
BRF	Bi-directional Reflectance Distribution
BRTF	Bi-directional Temperature Distribution Function
BTF	Bi-directional Temperature Distribution
Cab	Chlorophyll content
CHRIS	Compact High Resolution Imaging Spectrometer
CO <sub>2</sub>	Carbon Dioxide
DAIS	Digital Airborne Imaging Spectrometer
DGVM	Dynamic Global Vegetation Model
DIVERSITAS	International Programme of Biodiversity Science
ECMWF	European Centre for Medium Range Weather Forecasts
ESA	European Space Agency
ESSP	Earth System Science Partnership
EU	European Union
fAPAR	Fraction of Absorbed Photosynthetically Active Radiation
fCover	Fractional vegetation Cover as seen from nadir
FWHM	Full Width at Half Maximum
GCM	Global Climate Model
GCOS	Global Climate Observing System
GCP	Global Carbon Project
GMES	Global Monitoring for Environment and Security
GPP	Gross Primary Production
GtC	Gigatonnes Carbon
HYMAP	Hyperspectral Mapping
IGBP	International Geosphere-Biosphere Programme
IHDP	International Human Dimensions Programme on Global Environmental Change
IPCC	Intergovernmental Panel on Climate Change
ISCCP	International Satellite Cloud Climatology Project
ISLSCP	International Satellite Land-Surface Climatology Project
K	Kelvin
KP	Kyoto Protocol
LAI	Leaf Area Index
LIDF	Leaf Inclination Distribution Function

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LUE	Light Use Efficiency
LUT	Look Up Table
MERIS	Medium Resolution Imaging Spectrometer
MISR	Multi-angle Imaging Spectrometer
MODIS	Moderate Resolution Imaging Spectrometer
MODTRAN	MODerate resolution TRANSmittance radiative transfer model
NBP	Net Biome Production
NDVI	Normalised Difference Vegetation Index
NEdL	Noise Equivalent Delta Radiance
NEdT	Noise Equivalent Delta Temperature
NEP	Net Ecosystem Production
NIR	Near Infrared
NPP	Net Primary Production
NWP	Numerical Weather Prediction
PARCINOPY	A ray-tracing model of radiative transfer
PFT	Plant Function Type
POLDER	Polarisation and Directionality in Earth Reflectances
PROMET	PRocess-Oriented Multi-scale Evapo-Transpiration model
RE CAB	Regional assessment and modelling of the carbon balance of Europe
RMSE	Root Mean Square Error
SPECTRA	Surface Processes and Ecosystem Changes Through Response Analysis
SWIR	Short-Wave Infra-Red
TCOS	Terrestrial Carbon Observing System
TIR	Thermal Infrared
TOA	Top of Atmosphere
TOPC	Terrestrial Observation Panel for Climate
UNCCD	United Nations Convention to Combat Desertification
UNFCC	United Nations Framework Convention on Climate Change
VIS	Visible
WCRP	World Climate Research Programme
WUE	Water Use Efficiency





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