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EarthCARE - Earth Clouds, Aerosols and Radiation Explorer

WALES - Water Vapour Lidar Experiment in Space

WATS - Water Vapour and Temperature in the Troposphere and Stratosphere

ACECHEM - Atmospheric Composition Explorer for Chemistry and Climate Interaction

SPECTRA - Surface Processes and Ecosystem Changes Through Response Analysis

European Space Agency
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REPORTS FOR ASSESSMENT

THE FIVE CANDIDATE EARTH EXPLORER CORE MISSIONS

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September 2001

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SPECTRA – Surface Processes and Ecosystem Changes Through Response Analysis

European Space Agency
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ESA SP-1257(5) – The Five Candidate Earth Explorer Core Missions –
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 via two programmes: the Earth Observation Envelope Programme (EOEP) and the Earth Watch Programme. The Earth Explorer missions are completely covered by the EOEP.

There are two classes of Earth Explorer missions. The Core missions are larger missions addressing complex issues of wide scientific interest. The Opportunity missions are smaller missions in terms of cost to ESA, addressing more limited issues. Both types address the research objectives of the Earth Explorers, which are being implemented according to well established mechanisms (ESA, 1998). The missions are proposed, defined, evaluated and recommended by the scientific community.

Core and Opportunity missions are implemented in separate cycles. A new cycle is started every four years. The missions are implemented per cycle. The two missions selected in the first cycle of the Earth Explorer Core missions are underway: the Gravity field and steady-state Ocean Circulation Explorer (GOCE) and the Atmospheric Dynamics Mission (ADM-Aeolus), scheduled for launch in 2005 and 2007, respectively. The first cycle of Earth Explorer Opportunity missions is also on-going and will result in the CryoSat and Soil Moisture and Ocean Salinity (SMOS) missions to be launched in 2004 and 2006, respectively.

This report concerns the second cycle of Earth Explorer Core missions. As a result of the second call for ideas for Earth Explorer Core missions, which was released in June 2000, five missions were selected in Autumn 2000 for the second step of the implementation mechanism, i.e. the assessment. These missions are ACECHEM (Atmospheric Composition Explorer for CHEMistry and climate interaction), EarthCARE (Earth Clouds, Aerosols and Radiation Explorer), SPECTRA (Surface Processes and Ecosystem Changes Through Response Analysis), WALES (WAter vapour Lidar Experiment in Space), and WATS (WAter vapour and temperature in the Troposphere and Stratosphere). Reports for Assessment have been prepared for each of these candidate missions.

These reports will be circulated among the Earth Observation research community in preparation for the 'Earth Explorers Granada 2001 User Consultation Meeting', which will be held in Granada/Spain at the end of October 2001. The consultation meeting is part of the evaluation of the candidates that should lead to the selection of three candidates for feasibility studies in 2002-2003 and further to the selection of the next two Earth Explorer Core missions to be launched in 2008 (Core-3) and 2010 (Core-4).

This particular 'Report for Assessment' is concerned with the SPECTRA (Surface Processes and Ecosystem Changes Through Response Analysis) mission. It was prepared by a Core Mission Drafting Team consisting of four members of the SPECTRA Scientific Preparatory Group (SPG): Frederic Baret (INRA, Avignon, France), Massimo Menenti (University Louis Pasteur, Illkirch, France), David S. Schimel (Max Planck Institute Jena, Germany), and Michel M. Verstraete (Joint Research Centre, Ispra, Italy). They were supported by the other members of the SPECTRA-SPG, namely Wolfram Mauser (University of Munich, Germany), John R. Miller (York University, Canada), and Michael Schaepman (University Zürich-Irchel, Switzerland). Further scientific contributions to this report have been made by various other scientists, in particular by Gérard Dedieu, Bart van den Hurk, Stephen Plummer and Antonio José Sobrino.

The technical content of the report (notably Chapter 6) has been compiled by U. del Bello, J. Fuchs, J.-L. Bézy, and P. Silvestrin based on inputs derived from the industrial pre-Phase-A contractors and other supporting activities. Einar-Arne Herland and Alberto Tobias should also be acknowledged for their time and effort in reviewing this document, Pedro Baptista for editing the figures and Doris Reinprecht for preparing its publication.

Understanding the interactions between terrestrial ecosystems (in particular vegetation) and the atmosphere is a central requirement to address issues such as climate change and environmental degradation. Extensive scientific investigations over the past decades have demonstrated beyond doubt that the biosphere is tightly coupled to its physical environment (e.g. atmosphere and hydrosphere), and that it affects and is affected by the climate system, over a wide range of space and time scales. Yet, the likely evolution of our environment remains quite uncertain because of the number of relevant processes and the complexity of the issues involved (e.g. diversity of life forms, heterogeneity of the landscape). The release of carbon dioxide into the atmosphere by human activities has been recognised as one of the main drivers of climate change. Its partial sequestration by the biosphere in the form of net ecosystem productivity has both prevented even more drastic changes and provides a possible mechanism to counteract excessive releases. The scientific community is now being organised to address this central issue through an integrated observational and modelling approach. **The SPECTRA mission is particularly relevant and timely as a vehicle to implement this vision.**

The scientific objective of the SPECTRA mission is to describe, understand and model the role of terrestrial vegetation in the global carbon cycle and its response to climate variability under the increasing pressure of human activity.

The most evident characteristic of terrestrial biomes is heterogeneity over a range of spatial scales. The full complexity of these biomes is not well represented in global models of the Earth system, which are used to understand the overall functioning of the planet and to forecast its evolution. The key scientific issues in this respect include not only the description of the heterogeneity of representative landscapes, but also the analysis and prediction of how the underlying processes interact non-linearly across many scales to couple events at a local scale to changes at the global scale. To incorporate these processes and interactions in global models, they must be parameterised. This can only be achieved by documenting them at appropriate spatial and temporal resolutions, over an ensemble of regions representing all terrestrial biomes, including their functioning and heterogeneity. These regions will be selected before or during the mission, following scientific and programmatic criteria that will be defined by the scientific community, such as the presence of long-term monitoring equipment or the conduct of experimental campaigns. Remote sensing from space can complement these field investigations by offering unique capabilities to address such scaling issues, provided these observations are acquired at the appropriate spatial, temporal, spectral and directional resolutions. These measurements will provide a suitable basis to assess the role of local heterogeneity in determining processes and impacts at the regional scale albeit through parameterisations, in global biosphere and climate models.

Models exist today to assimilate remote sensing measurements from low-resolution sensors. In the near future, Earth System Models (ESMs) will include explicit dynamic representations of the biosphere and carbon cycle. They will require much better parameterisations of surface processes at scales of tens of kilometres and need to be generated for all relevant biomes. This can only be achieved through a better understanding of how physical, chemical and biological processes interact non-linearly over heterogeneous land surfaces. The availability of detailed observations such as those provided by SPECTRA will thus present new opportunities to derive simple yet sufficiently accurate representations of the terrestrial biosphere for use in global ESMs.

The SPECTRA mission will provide detailed observations of the amount and condition of vegetation over an ensemble of regions distributed globally. These observations are needed to derive the biome-specific parameterisations of biosphere processes needed by Dynamic Global Vegetation Models (DGVMs). These parameterisations, together with a suitable biome distribution, will enable the derivation of global estimates of carbon fluxes, using existing and future sensors offering a lower spatial resolution, but frequent global coverage.

The SPECTRA mission will be able to capitalise on the achievements of various earlier Earth-observation missions. The state and evolution of the Earth system (climate and biosphere), and in particular of the terrestrial biomes, have been monitored from space over the last twenty years or so with the help of various sensors onboard Earth-observation platforms. These missions (notably NOAA/AVHRR, Meteosat, SeaWiFS, VEGETATION, POLDER) provide essential global observations on a daily basis, in a very limited number of spectral bands and at a coarse spatial resolution. The current generation of coarse resolution global instruments (e.g. MODIS, MISR, MERIS, AATSR, SEVIRI) offers enhanced spectral and directional sampling capacities along with high radiometric performances, but still at medium spatial resolution. These observations provide broad estimates of vegetation and soil variables. The continued availability of remote-sensing data at spatial resolutions from hundreds of metres to a few kilometres, on a global and daily basis, can be expected for the foreseeable future, because of the large number of applications that are relying on them.

To meet the scientific objective presented earlier, the SPECTRA mission will acquire detailed spectral and directional measurements of the reflectance and emittance of the heterogeneous land and atmosphere system, at a high spatial and radiometric resolution, and with a revisit frequency sufficient to document the often rapid evolution of terrestrial vegetation.

No current or planned mission will provide the detailed measurements required to address the scientific objective of the SPECTRA mission, with the requisite spatial, temporal, spectral, directional and radiometric resolutions described in this Report.

SPECTRA benefits from the extensive **scientific know-how** accumulated over the last decade, both in terms of algorithms and applications.

The SPECTRA mission consists of three elements: The **space segment** comprises a platform in a near-polar orbit to allow repeated data acquisitions and global accessibility, and a sensor providing the required radiometric, spatial and directional performances in a wide spectral domain encompassing the visible, near-infrared, middle-infrared and thermal-infrared. The **ground segment** involves facilities for the management of the satellite, the acquisition of raw data and the production of basic geophysical products, addressing such generic issues as calibration, navigation, co-registration, etc. It is anticipated that the dedicated data processing for specific applications and the archiving of intermediate and final products will take place in institutions of high scientific calibre. The **field segment** of SPECTRA will guarantee effective integration of *in-situ* measurements with SPECTRA data products over an ensemble of regions, globally distributed to sample all relevant biomes.

In summary, the SPECTRA mission addresses scientific objectives of great relevance, proposes a combined spaceborne and field observational strategy, offers a technical solution that meets the observational requirements and capitalises on a vast array of existing experimental and theoretical know-how. This mission will prove useful to a wide diversity of users and poses no major technical difficulty.

All 'Reports for Assessment' follow a common general structure comprising seven chapters. Following this Introduction, this report is organised as follows:

- Chapter 2 addresses the background and provides the scientific justification for the mission, set in the context of issues of concern and the associated need to advance current scientific understanding. The chapter identifies the problem and gives the relevant background. It provides a clear identification of the potential 'delta' this mission would provide.

- Drawing on these arguments, Chapter 3 discusses the importance of the scientific goal of the mission, identifies specific research objectives, and describes how the proposed methodological approach leads to the required measurements, highlighting the unique contribution of the mission.

- Chapter 4 derives the observational requirements from the measurement needs identified in Chapter 3 through a detailed analysis of algorithm performance.

- Chapter 5 provides an overview of the mission elements, including the space, ground and field segments. It also identifies the need for external ancillary data sets, and discusses the contribution of this mission to other Earth-observation missions.

- Chapter 6 provides a concise description of the proposed technical concept (space and ground segments), establishes basic system feasibility and provides a preliminary assessment of the expected performances of the system.

- Chapter 7 outlines programme implementation, including risks, and the expected development schedule. It also discusses SPECTRA in the context of other related missions.

2 Background and Scientific Justification

2.1 Scientific Context

There is strong observational evidence that the Earth's climate is changing rapidly, and a widespread consensus attributing these changes to human activities (IPCC, 2001). The primary consequences include a temperature increase resulting in the so-called 'global warming', the progressive elevation of mean sea level and more frequent and severe extreme events such as flooding, drought, and cyclones. These effects, in turn, begin to seriously affect societies and economies. Major concerns about the evolution of the coupled climate-biosphere system, have put a premium on the provision of reliable, accurate information, and therefore on the advancement of the underlying science.

In particular the recent but continuously increasing concentration of atmospheric CO_2 and other carbon compounds (CH_4, CO, volatile carbon compounds) contributes to the greenhouse effect by trapping the long-wave radiation emitted by the surface.

The carbon cycle is thus one of the key issues to be investigated in order to properly understand climate change on a global scale. The global carbon cycle connects the three major components of the Earth system: the atmosphere, the oceans and the land surfaces. Each of those components stores significant quantities of carbon, of which a relatively small fraction is exchanged (Figure 2.1). For many centuries prior to the industrial revolution, the carbon pools were more or less in equilibrium, and the net transfers between these reservoirs were close to zero over sufficiently large areas or, in the case of smaller areas, over a sufficiently long period of time. An epochal change occurred following industrialisation, with the accelerated transfer of carbon from the geological pool (fossil fuels) to the atmosphere through direct burning or from the emissions associated with land-use changes (deforestation, desertification, biomass burning, etc). Because of these connections among pools, an increased atmospheric carbon concentration also affects the other major carbon reservoirs in oceans and over land (Figure 2.1).

Human activities (fossil fuel burning, cement production and land use changes) release around 7.9 Gt of CO_2 into the atmosphere yearly, 42% of which contributes to increasing its CO_2 concentration by about 1.5 ppm per year (Figure 2.2). The remaining part is approximately equally absorbed by the ocean and terrestrial components. The processes governing the fluxes between the pools take place at various rates and temporal scales, from daily to centennial and longer. The diversity and complexity of the controlling processes, as well as their non-linear interactions, make the characterisation of the carbon cycle and the prediction of its evolution and impacts very challenging. This is especially the case in view of the large uncertainties associated with current estimates of the contents of reservoirs, and of fluxes between them (Figure 2.1).

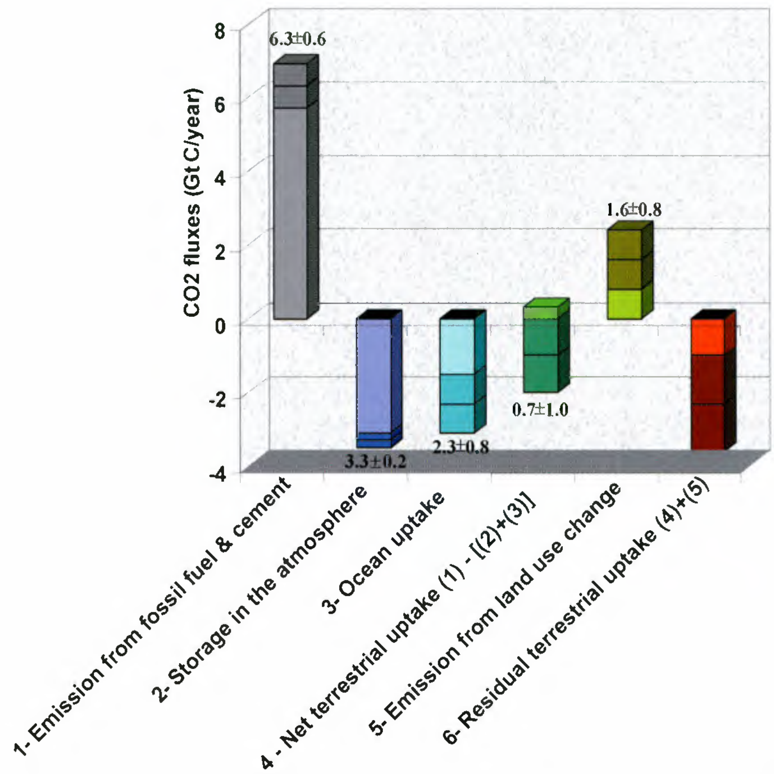

Figure 2.1: *Schematic of the carbon cycle, pools and fluxes, with the associated uncertainties (darker colour). Data from the IPCC report (IPCC, 2000), for the period 1989 to 1998.*

The spatial and temporal variability of CO_2 fluxes is very large, particularly over land, as compared to the ocean or the atmosphere (e.g. Braswell et al., 1997; Heinman and Kaminsky, 1999; Rayner et al., 1999). It is largely driven by changes in biome distribution, soils, and climate conditions, as well as human actions and disturbances. Uncertainties are particularly large over land areas, because of the heterogeneity of the environment, the intrinsic difficulties in adequately sampling the relevant variables and the limitations of existing models. Research centred on reducing these uncertainties, and in particular on assessing the strength of the terrestrial carbon sink, is thus mandatory.

Current models cannot reconcile conflicting observations of the annual carbon budget at the global level, especially with regard to the stocks and fluxes over land. It is not even possible to determine the spatial distribution of carbon sinks on regional to national scales accurately enough for policy making. International research institutions have recently highlighted the need for enhanced experimental and monitoring systems (flux measurements, satellite sensors, field and laboratory experiments, global data archives). When available, the data generated by these observational systems will permit the development of better parameterisations, which, in turn, will allow much more accurate assessments and forecasts of the climate and global carbon cycle (Cramer et al., 1999).

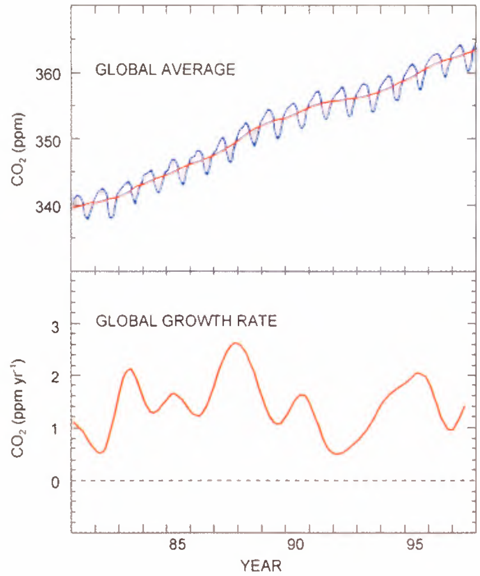

Figure 2.2: *Temporal variations of CO_2 concentration and growth rate in the atmosphere over the last two decades, as determined from the NOAA CMDL cooperative air-sampling network.*

The scientific objective of the SPECTRA mission is to describe, understand and model the role of terrestrial vegetation in the global carbon cycle and its response to climate variability under the increasing pressure of human activity.

2.2 Global Environmental Policy

Policy instruments, including the Kyoto Protocol, the UN Framework Convention on Climate Change (UNFCCC) guidelines on national greenhouse inventories, the Convention to Combat Desertification and the Biodiversity Convention, have been established to mitigate the effects of climate change and human-driven perturbations on our environment. In this context, the carbon cycle constitutes a central issue. The Kyoto Protocol to the UNFCCC, although not yet ratified by all countries, proposes a global policy to be applied at the national level, based on assessments of carbon emission and sequestration rates. The aim of the Kyoto Protocol is to stabilise the CO_2 concentration in the atmosphere in the long run. Several mechanisms are envisaged, including the commercial trading of emission rights, the reduction of emissions from fossil fuel combustion, for instance through the development of less polluting technologies and their implementation in both developed and developing countries (clean development mechanism), as well as the enhancement of natural sinks.

The consideration of carbon sinks in the Kyoto Protocol has given rise to a multitude of questions. Increasing the strength of the biological sinks is technically feasible, but it is challenging to devise and implement a scientifically sound accounting and verification system. The key specific issues to be resolved within this framework are (Valentini et al., 2000):

- ***Variability:*** How variable is the terrestrial part of the carbon cycle in time and space?

- ***Uncertainty:*** How well can we measure the actual sink strength of the biosphere over land?

- ***Attribution:*** What processes are causing the terrestrial biosphere to take up carbon at the current high rates?

- ***Non-permanence:*** How long does the carbon stay in a particular pool?

- ***Leakage:*** Does carbon sequestration at a given location lead to additional CO_2 emissions elsewhere?

- ***Future:*** How will carbon sequestration in the terrestrial biosphere evolve?

The Kyoto Protocol requests signatory countries to report CO_2 sequestrations in a transparent and verifiable manner. The estimated carbon up-take of the biosphere must be consistent with all other available evidence at three levels of integration of the carbon budget:

- All estimates of stocks and fluxes must ultimately permit the closure of the **global** carbon cycle.

- **National** (or European) accounting is required by international treaties, with an accuracy sufficient to focus discussions on policies and implications rather than on uncertainties.

- It must be possible to definitely close the **local** carbon balance over intensively studied regions, provided models and observations are adequate.

While theoretical and experimental investigations are proceeding on many fronts, the difficulties associated with the effective description of spatial heterogeneity and the coupling of subsystems across multiple scales have been identified as one of the most limiting factors on achieving these objectives. The SPECTRA mission has been conceived to directly address these issues, either by providing the required observational data or by supporting the development of appropriate parameterisations suitable for global models. This is particularly relevant in the context of the Global Monitoring for Environment and Security (GMES) initiative proposed by the European Commission, ESA, and a variety of national and private partners.

2.3 International Programmatic Context

Research into the global carbon cycle is organised through national, multi-national and international research networks. The International Geosphere Biosphere Programme (IGBP) and the World Climate Research Programme (WCRP) provide a strong international framework for observational and modelling studies of the carbon cycle. The WCRP coordinates the international network of atmospheric observations, while the IGBP is responsible for terrestrial and oceanic studies through several core projects. Specifically, the Joint Global Ocean Flux Study (JGOFS) contributed significantly to the assessment of the oceanic part of the carbon cycle, while the Global Change and Terrestrial Ecosystems (GCTE) and the Biological Aspects of the Hydrological Cycle (BAHC) core projects investigated water and carbon fluxes, as well as their interactions, over land. The Global Analysis Interpretation and Modelling (GAIM) core project, for its part, supports the development of integrated tools and techniques to analyse the observations available. More recently, IGBP has been refocussed with three main themes: the carbon cycle and associated issues, the water cycle and water resources, and the sustainable production of food and fibre.

Since the early 1990s, international organisations have been working towards the establishment of long-term observing systems for the three main components of the Earth system: terrestrial environment, oceans, and atmosphere. The need for such observing systems was evident during the preparation of the 1992 United Nations Conference on Environment and Development, when scientists and policy makers were hindered by a lack of key data and information upon which to base targets and performance goals. The emerging global observing systems for oceans (GOOS: Global Ocean Observation Strategy), terrestrial environment (GTOS: Global terrestrial Observation Strategy), and climate (GCOS: Global Climate Observation Strategy) are intended to complement the existing atmospheric observation capabilities implemented as part of the Global Atmospheric Watch (GAW) through WMO. Like GAW, GTOS, GCOS and GOOS are also designed to include space and *in-situ* components. Given the diversity of landscapes, this strategy is essential, because Earth observation from space is the only observational approach capable of providing data at the scales and resolutions needed to extrapolate the findings of local field studies to larger areas, to document the heterogeneity of the landscape at the regional scale, and to connect these findings into a global view. The close co-ordination of satellite and *in-situ* observational programmes is thus essential for the successful realisation of these observing systems.

Plans are currently under way to coordinate existing and future observations of the carbon cycle, through such national or multinational programmes as the European Carbo-Europe and Euro-Sib projects, providing coverage of Europe and Russia, CERN for China, the US Carbon Science Plan and the Brazilian-led LBA project for Amazonia. The programmatic approach is increasingly based on the creation of networks of surface and airborne flux observations, plant and soil process studies, and *in-situ* experiments, as well as model evaluations through inter-comparisons. This is exemplified by the recent proposal by IGBP, IHDP and WCRP to coordinate a joint project called 'The Carbon Challenge' (Hibbard et al., 2001).

Space agencies and international organisations dealing with both observational and research programmes have recently established a new co-ordination mechanism, the Integrated Global Observing Strategy Partnership (IGOS-P) that will facilitate progress in space-based measurements. The IGOS-Partnership includes GCOS, GTOS, GOOS, WCRP, IGBP, ICSU, FAO, UNEP, IOC, WMO, UNESCO, IGFA and CEOS, all of which have signed a formal letter of partnership acknowledging their commitment to work together in the context of the Integrated Global Observing Strategy. IGOS-P has chosen to proceed by themes, rather than projects, with agreed criteria being established for the selection of those themes. In June 1999, IGOS-P agreed to consider a proposal for a terrestrial carbon theme by GTOS. The GTOS/GCOS Terrestrial Observation Panel for Climate (TOPC) decided to establish the overarching Global Carbon theme. The Terrestrial Carbon Observation (TCO) theme defines observation requirements for an accurate estimation of the distribution of terrestrial carbon sources and sinks of the world at high spatial and temporal resolutions. The aim of the TCO theme is to provide the scientific community with the appropriate data sets to be able to produce global carbon flux maps at the regional scale.

The results of the ongoing work within the TCO were presented at a workshop in February 2000 in Ottawa and can now be used as a science-based guideline for the observational requirements for an accurate estimation of the distribution of terrestrial carbon sources and sinks around the World with high spatial and temporal resolutions. The definition of the proposed SPECTRA mission was directly inspired by these recommendations.

2.4 Processes of Interest

2.4.1 Terrestrial Carbon Cycle: An Overview

The terrestrial carbon cycle can be studied on a range of space and time scales, resulting in nested fluxes as illustrated in Figure 2.3.

- **GPP:** Gross Primary Productivity refers to the rate of fixation of atmospheric CO_2 into biomass through the photosynthesis process. This corresponds to a short-term (i.e. minutes to hours and days) transfer of carbon from the atmosphere to the biosphere.

- **NPP:** Net Primary Productivity designates the net uptake of carbon by the biosphere when its (autotrophic) respiration has been discounted from the GPP. Time scale is similar to that of GPP.

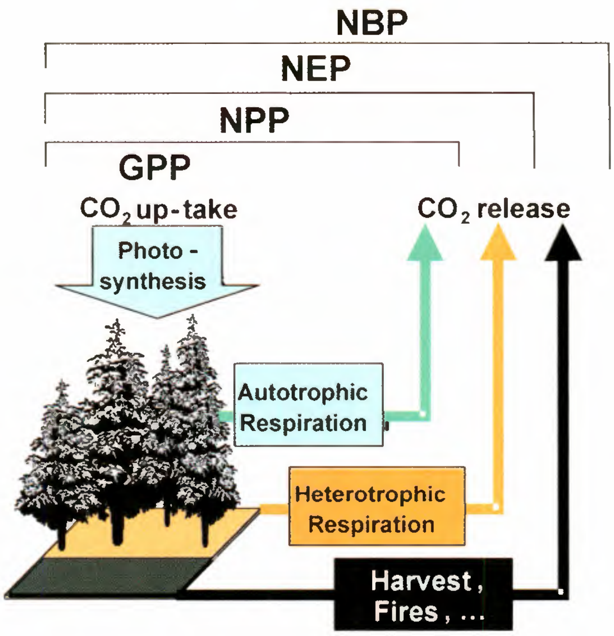

Figure 2.3: *Schematic of the processes determining CO_2 fluxes in terrestrial biomes on various time scales (adapted from art-work produced by IGBP).*

- **NEP:** Net Ecosystem Productivity represents the actual rate of accumulation of carbon in the terrestrial biosphere after soil (heterotrophic) respiration has been accounted for. NEP must necessarily be evaluated over longer periods than those required to decompose dead organic materials, i.e. months to years.

- **NBP:** Net Biome Productivity is calculated by discounting losses of carbon due to harvesting or natural hazards such as fires. As for NEP, stable estimates of NBP can only be obtained for periods longer than the characteristic time scales of these events, i.e. years to decades and centuries.

2.4.2 Processes and Interactions: Why Parameterisations are Biome-Specific

The role of parameterisations in complex models of the terrestrial carbon cycle, and their biome-dependent nature, is evident from the following equations, which describe in a simple yet illustrative way how the energy, water and carbon fluxes are related.

Energy. The relative magnitudes of heat fluxes between the land surface and the atmosphere determine the so-called 'evaporative fraction' Λ:

$$\Lambda = \frac{LE}{R_n - G} \tag{2.1}$$

where LE, R_n and G are the latent heat, net radiation and soil heat flux densities, respectively. Furthermore, $R_n - G = LE + H$, where H is the sensible heat flux density. All of these flux densities are expressed in Wm^{-2}. In practice, all Land Surface Models estimate H on the basis of the difference in temperature between the land surface and some reference level in the atmosphere, using a suitable parameterisation. Similarly, the evaporation rate is derived from the observed gradient in the free energy of water. The physical processes represented in this way include molecular diffusion, as well as forced and free convection. The geometrical and thermal heterogeneity of the surface further affects heat transfer in complex ways. Commonly used parameterisations of heat transfer involve aerodynamic resistances for momentum transfer, and for heat transfer.

Water. The determination of simple relationships with which to compute H from commonly available data, such as surface and air temperature, has been the focus of many Land Surface Experiments (LSE). Once H and LE have been determined as explained above, Λ can also be determined, assuming that G is known or negligible. Since $R_n - G = LE_{max}$, the evaporative fraction provides an estimate of the canopy resistance r_c, (or the associated conductance) to the exchange of water vapour between vegetation and atmosphere:

$$\frac{LE}{LE_{max}} = f(r_c) \tag{2.2}$$

where $f(r_c)$ is a parameterisation of the processes limiting water transfer from the soil to the atmosphere through vegetation canopies. A time series of values can be used to relate canopy resistance to other environmental variables, such as solar radiation and atmospheric water vapour pressure deficit. Such parameterisations of the land-atmosphere exchange of water vapour are used, for instance, in soil water balance models.

Carbon. The accumulation of carbon in terrestrial vegetation is related to the net exchange of CO_2 between plants and atmosphere through leaf stomata. To the first order, the CO_2 flux can be parameterised using the same canopy resistance r_c that is used to parameterise the flux of water vapour through the stomata. By analogy, the CO_2 flux is usually estimated from the difference in CO_2 concentration between air in the leaf stomata and some reference level in the atmosphere above the canopy:

$$F_C = \frac{(c_s - c_a)}{r_c} \tag{2.3}$$

The canopy resistance r_c is also commonly related to other environmental variables to represent the effects of processes reducing the ability of terrestrial vegetation to convert radiant energy into carbohydrates. These relationships are known as the Jarvis-Stewart model:

$$r_c = \frac{r_{c,min}}{LAI \, . \, F_1(K^{\downarrow}) \, . \, F_2(T_a) \, . \, F_3(\Delta e) \, . \, F_4(\Psi)} \tag{2.4}$$

where $r_{c,min}$ is the minimum canopy resistance, $K^{\downarrow}$ is the incoming global solar radiation, T_a is the temperature of the air at the selected reference level, Δe is the atmospheric water vapour pressure deficit, and Ψ is soil water potential. The F_i are empirical functions (parameterisations) of the relevant stress factors. These relationships are highly biome-specific and, in some cases, time-dependent.

Since the canopy resistance r_c controls both the evaporation and the carbon fluxes, they are related. Empirical evidence suggests that the relation is reasonably linear, at least to a first order (see Figure 2.4):

$$F_C \cong a \cdot LE \tag{2.5}$$

It is reasonable to assume that different values of a should be used for different vegetation types and at different times. The equations above indicate that a is related to environmental and plant properties as:

$$a = \frac{1}{r_c f(r_c)} \cdot \frac{(c_s - c_a)}{LE_{max}} \tag{2.6}$$

As mentioned earlier r_c and $f(r_c)$ are semi-empirical functions of canopy properties (i.e. parameterisations of canopy processes), the vertical gradient of carbon dioxide $(c_s - c_a)$ does not vary rapidly in time, and LE_{max} has been shown to depend on climate variables, as well as LAI and surface albedo (Stanghellini et al., 1990; D' Urso, 2001).

The canopy resistance r_c, which effectively parameterises the complex role of terrestrial vegetation in determining the exchanges of energy, water and carbon, is extensively used in state-of-the-art models of the Earth-atmosphere system. Yet, since the spatial and temporal variability (Figure 2.5) of r_c is significant, using space and time-independent values carries significant risks to generate products or information of poor accuracy.

The linear relations exhibited in Figure 2.4 allow the production of regional patterns of F_C on the basis of patterns of LE (Figure 2.6). This relationship has been used to produce maps of F_C for some of the MEDEFLUX (EUROFLUX) sites (Roerink et al., 2001) and during the DAISEX campaign (ESA, 2001a), using the spatial distribution of LE derived from the Surface Energy Balance Index (SEBI) (Menenti and Choudhury, 1993).

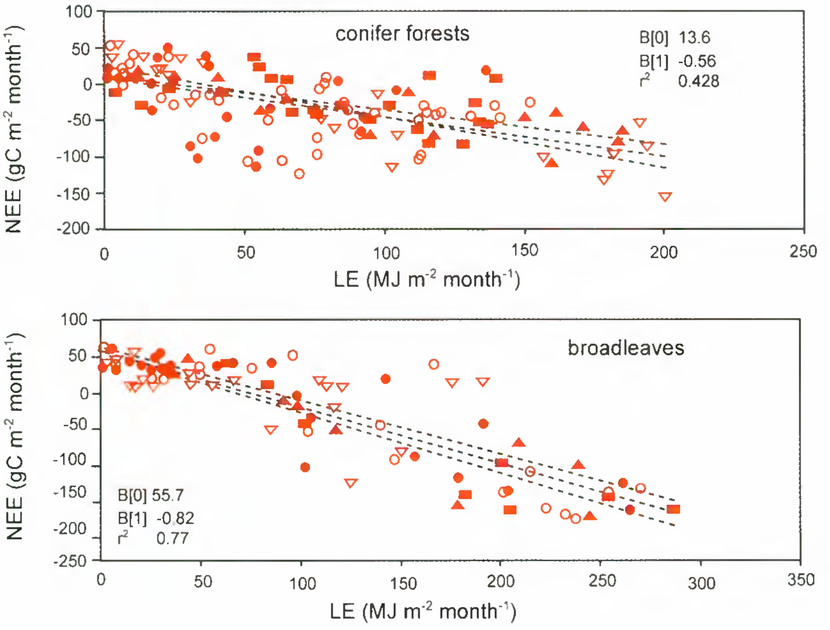

Figure 2.4: *Relationship between the latent heat flux, LE (the evaporation of water into the atmosphere) and net ecosystem exchange, NEE (equivalent to NEP, with negative values indicating a sequestration of atmospheric carbon into the biosphere) for two biome types. The various symbols represent sites located in different biomes.*

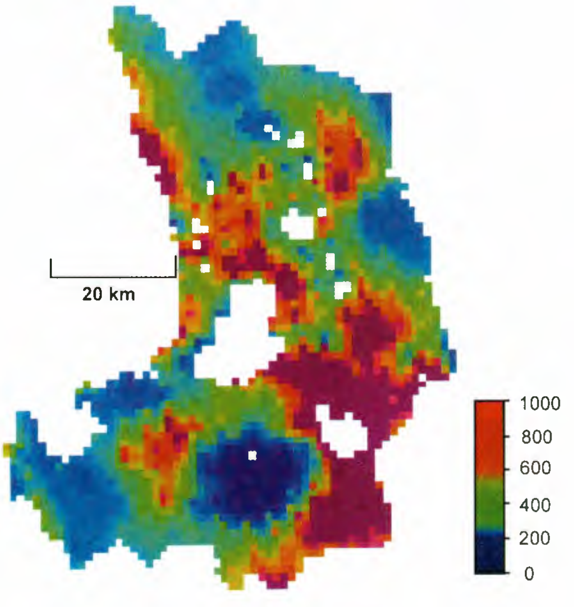

Figure 2.5: *Estimates of canopy conductance $g = 1/r_c$ derived from NASA's Landsat Thematic Mapper data over a watershed in Kenya, using the equations given in the text (Farah, 2000).*

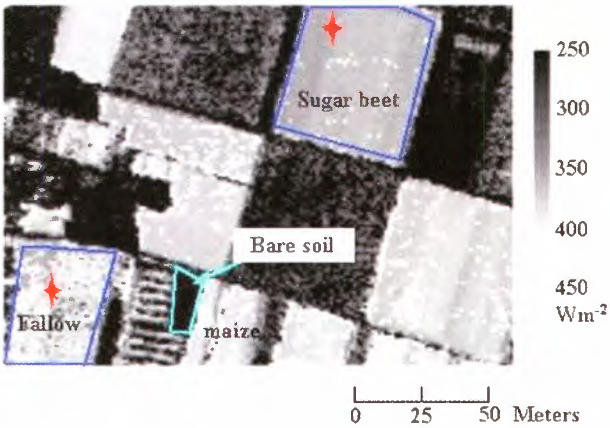

Figure 2.6: *The distribution of latent heat flux density LE over various canopy types; crosses (red) indicate the locations of field measurements. Data source: DAISEX airborne campaign over Colmar, France, 19 July 1999 (http://io.uv.es/projects/daisex).*

The above examples are based on the use of field and remote-sensing observations of surface temperature, albedo, fractional cover and Leaf Area Index, where the spatial resolution of directional spectro-radiometric data acquired from space is high enough to be compatible with field investigations, and where the area covered is large enough to document the state (including the heterogeneity) of a representative region within the observed biome.

The spatial variability of the CO_2 flux has three significant implications:

- accurate calculations of area-integrals of F_C need to be based on the actual spatial distribution of vegetation properties, because of the combined effect of the heterogeneity of terrestrial landscapes and the non-linearity of energy, water and carbon exchange processes (see, for example, Pelgrum, 2000);
- the responses of different vegetation types (biomes) to weather and climate cannot be understood on the basis of local flux measurements; and
- the effectiveness of different land uses in terms of carbon sequestration can only be assessed if F_C is known for each land-use type separately.

Thus the relation between climate and vegetation response (in terms of water and carbon exchanges) is biome-specific and exhibits significant spatial and temporal variability. Global models of the Earth system do not yet take into account the vegetation-specific response to climate variability. ***The knowledge needed to do so will be built upon the observations to be provided by SPECTRA and the global networks of research sites.***

2.4.3 Biosphere Processes Controlling the Terrestrial Carbon Cycle: Key Variables, Models and Scales

In the following, the main driving variables of the previously mentioned processes are briefly identified. Quantities that can be derived from the radiometric observations of a mission such as SPECTRA are highlighted in bold:

- ***Photosynthesis*** is the process by which vegetation fixes atmospheric carbon dioxide into biomass, using solar energy. The rate of carbon fixation by the vegetation depends first and foremost on the amount of photosynthetically active radiation (PAR, nominally between 400 and 700 nm), absorbed by the canopy (McCree, 1972). The **fraction of Absorbed PAR** (fAPAR) depends on the **architecture** of the canopy and on the **optical properties** of its elements (leaves, stems, trunks, branches, background) (e.g. Sellers, 1985). Canopy architecture is traditionally described by the **Leaf Area Index** (LAI: the total one-sided leaf area of the canopy per unit horizontal ground area), although more sophisticated representations of leaf clustering in plants and plant clumping are emerging. The efficiency with which the PAR energy absorbed by the canopy is actually transformed into biomass depends strongly on species, phenology and the environmental conditions experienced by the vegetation. Atmospheric carbon dioxide is transferred to chloroplasts (where the chlorophyll molecules are located and photosynthesis takes place) through small holes in the leaf surface called stomata. Plants control the opening and closing of their stomata, and thereby regulate the rates at which carbon dioxide molecules enter and water molecules exit these stomata. Since both photosynthesis and evaporation of liquid water in the stomata require significant energy inputs, the carbon, water and energy cycles are intimately linked through the suite of chemical and biological mechanisms associated with the primary productivity of plants. These relationships are biome-dependent, as illustrated in Figure 2.4. It is therefore essential to describe concurrently the water, energy and carbon exchanges in order to be able to understand photosynthesis. The rate of photosynthesis also depends on many other factors, including carbon dioxide concentration in the atmosphere, **leaf temperature,** or mineral deficiencies (in particular nitrogen) in the soil. The nitrogen content of leaves is strongly related to their **chlorophyll content** (Field and Mooney, 1986).

- ***Autotrophic respiration*** is the process by which some of the chemical energy stored by photosynthesis is used by the plants themselves to grow and develop. This process is critical to the carbon cycle because it results in the rapid release of a large fraction of the carbon initially stored through photosynthesis back to the atmosphere. Autotrophic respiration depends on **foliage temperature**, growth rates and total biomass, as well as on the biochemical composition of the products formed in the plants.

• ***Heterotrophic respiration*** is the process by which some of the carbon stored in organic soil components is released. The soil carbon reservoir can be very large compared to the above-ground biomass. Understanding the fluxes of carbon to (senescence, mortality) and from (respiration or mineralisation) this soil reservoir becomes a major issue when closing the carbon cycle at the local scale (Figure 2.7). Heterotrophic respiration is very dependent on **soil temperature**, and the **availability of water** and nutrients, particularly nitrogen. Apart from nitrogen fertilisation or deposition, symbiotic fixation of atmospheric nitrogen, and leakage or volatilisation, the nitrogen cycle is intimately linked to the carbon cycle within the soil via the biotic activity. Evaluation of heterotrophic respiration is a major challenge in the description and modelling of NEP.

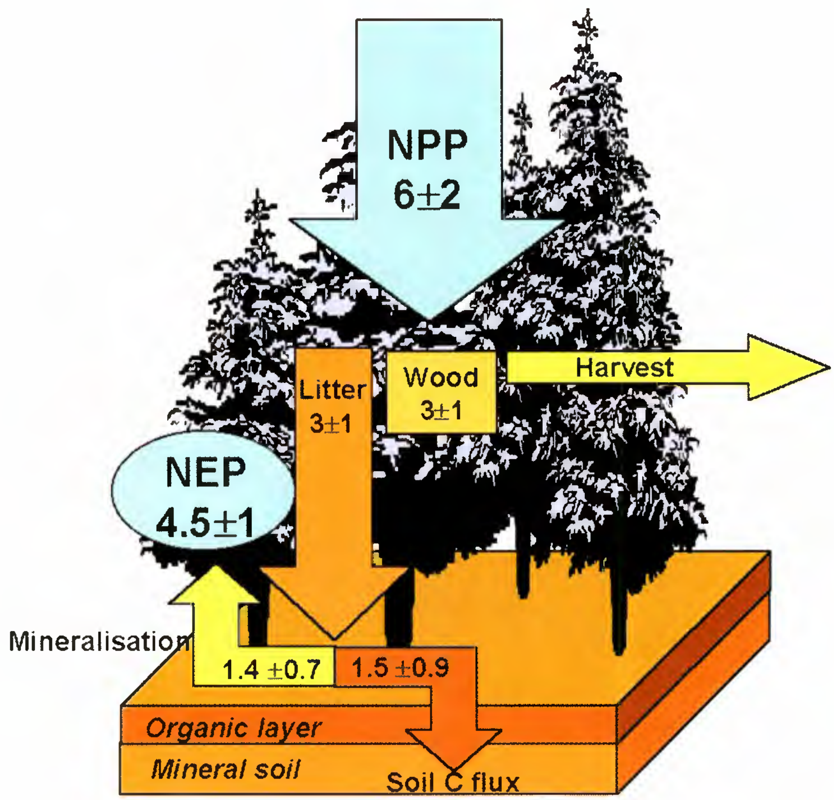

Figure 2.7: *Typical values of carbon fluxes (t C ha^{-1} yr^{-1}) observed over forest ecosystems, and their associated uncertainties. (Adapted from Valentini et al., 2000).*

• ***Water and energy*** both play a critical role in plant physiology, as seen above. Water is used by plants to transport nutrients from the soil through the roots, to the various plant organs, to redistribute assimilates within and between these organs, to control structural stability and optimise solar radiation interception (through turgescence) and to ensure the thermal regulation of plant tissues. The soil constitutes the main reservoir of water for plants. This reservoir is mainly replenished by rainfall, flooding, irrigation or capillary rise from a lower water table. Conversely, water losses are due to evaporation from the soil, extraction of water by the roots to support plant transpiration, run-off and drainage. Evaporation and transpiration are often combined into evapotranspiration to describe the total water flux to the atmosphere. Of course, the water and energy cycles are also closely linked through the latent heat needed to evaporate liquid water in plants or in the soil. The energy balance, in turn, is primarily driven by the available incident solar energy (both direct and diffuse radiation). In the solar domain (300 to 3000 nm), the **bi-directional spectral reflectance** of the soil and canopy control how much radiation is actually available at the surface. The radiative energy absorbed by the plants but not used in photosynthesis and the energy absorbed in soils are transformed into heat and ultimately released to the environment through conduction, convection (sensible and latent heat fluxes), or thermal emission. The last is controlled by the relevant temperature and emissivity. The convective fluxes are largely determined by gradients of temperature (sensible heat flux) or humidity (latent heat flux), and by a variety of complex mechanisms collectively represented through empirical coefficients, known as resistances, that depend on **leaf area index** and **vegetation type** (Menenti and Ritchie, 1994).

- ***Ecosystem dynamics***. Many of the processes described above are dependent on the type of ecosystem or biome considered. Ecosystems are built from a collection of species that are organised according to complex rules. In fact, ecosystems tend to adapt themselves to the local soil and climatic conditions, and develop specific strategies for surviving, always being subject to the competition of a wide range of species. Whenever external conditions are changing, either due to climatic variability, fire or human activities, the fragile equilibrium between species may shift, leading to changes in the ecosystem functioning and composition. In the absence of direct human interference by deforestation, fire and agriculture, this process is generally slow and can be observed only over long time periods or along specific pedo-climatic gradients. However, when simulating long-term climate changes, these processes become very important and must be accounted for (Prentice et al., 1989; Steffen et al., 1992).

These processes are explicitly represented in models (Figure 2.8) that may be classified as follows:

Land Surface Models (LSM) describe physiological and biophysical processes, as well as soil biochemical and physical processes. Exchanges with the atmosphere are described by a Soil Vegetation Atmosphere Transfer (SVAT) module that runs under forced climatic conditions. In these models, soil properties such as temperature, moisture and nitrogen content vary with time, but all other characteristics are supposed to be stable (e.g., Brisson et al., 1998; Spitters, 1989; Hoogenboom et al., 1998). Some of these LSMs include a radiative transfer module to simulate the reflectance of the

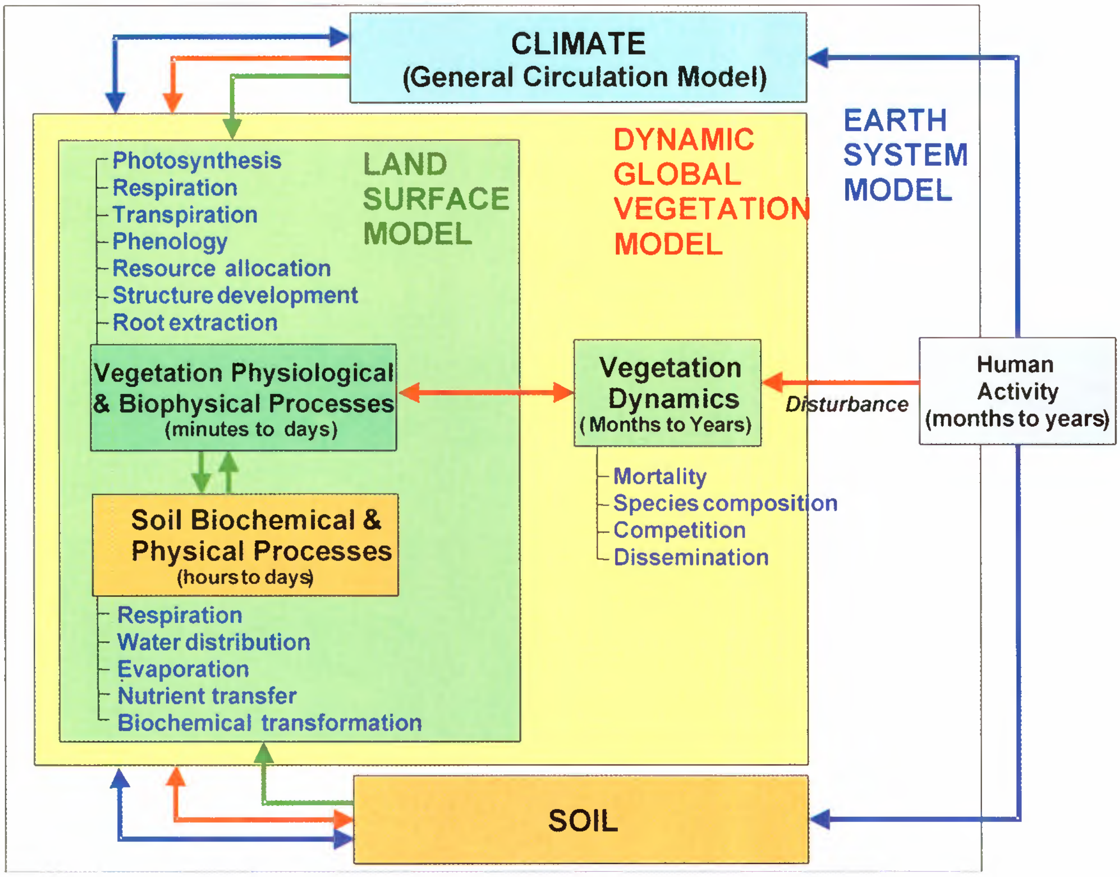

Figure 2.8: *Schematic of the processes determining the interactions between vegetation and the climate system, at various space and time scales, and of the types of models needed to describe them.*

canopy, they can be used to assimilate radiance measurements gathered from space (e.g. Weiss et al., 2001; Schneider, 1999).

Dynamic Global Vegetation Models (DGVM) typically include an LSM and an additional module that describes the dynamic evolution of the ecosystem as a function of climatic variables. Interactions with soil properties may be included to describe the dynamics of variables other than temperature, moisture and nitrogen content. However, they are still running under forced climatic conditions. They differ significantly in complexity and reliance on parameterisations. Simpler models are more efficient, but also more limited to describe particular processes. They are suitable for long-term studies or to investigate feedbacks in coupled Earth System Models (Cox et al., 2000). On the other hand, more complex models allow for direct studies of eco-physiological processes and their implications on a global scale. Cramer et al. (2001) recently reviewed and compared various DGVMs. The differences in model complexity and reliance on parameterisation lead to large uncertainties in the terrestrial carbon balance.

Detailed remote-sensing observations with high resolution will be critical to improve these parameterisations and evaluate the performance of these models.

Earth System Models (ESM) attempt to couple all the relevant processes together, with an emphasis on the atmosphere-surface interactions. They focus on the global spatial scale, and are used to simulate the evolution of the entire system over time scales of up to decades. These models necessarily rely on effective parameterisations of small-scale processes; their results are thus very sensitive to the accuracy of these parameterisations.

This discussion has identified a range of variables relevant to describing the state and evolution of the land surface. Some of them (highlighted in bold in the preceding sections) can be retrieved from an analysis of radiometric measurements made in space, and used in combination with these models.

The exploitation of remote-sensing observations can follow two different approaches. In the first one, **forcing**, biophysical variables such as those identified above (e.g., fAPAR, LAI, soil temperature, etc.) are determined from radiance measurements and put directly into the models. The second approach consists of the **assimilation** of either geophysical products or radiometric measurements into dynamic models. This is achieved by adjusting one or more model parameters until the model matches the observations.

Each approach has its advantages. Data assimilation guarantees a high degree of internal model consistency, may be less sensitive to gaps in the data sets (such as produced by the obscuration of the surface by clouds) and may lead to the determination of optimal solutions. In the case of forcing, satellite data can be analysed off-line with generally more detailed radiative models to generate products independent of the type and sophistication of the environmental models that may use this information. Data assimilation may lead (see examples in Chapter 3) to the parameterisation of complex biome properties, such as canopy conductance for gas exchange. Observations of leaf water content and leaf dry matter are useful for this purpose. Improved parameterisations may be used to forecast long-term trends, when sparse or even no concurrent data are available.

The SPECTRA mission is designed to provide high accuracy estimates of the variables shown in Table 2.1, on spatial and temporal scales appropriate to support local field studies, up-scaling investigations to the regional scale as well as the refinement and evaluation of parameterisations suitable for global scale models.

2.5 Approaches Used to Describe the Carbon Fluxes

The scientific community is currently using one of two approaches to describe and understand the carbon fluxes between terrestrial surfaces and the atmosphere, known as the top-down and bottom-up approaches. They have been reviewed at a recent workshop on the terrestrial component of the carbon cycle (Cilhar et al., 2000).

Variables Remotely Sensed	Forcing	Assimilation
Biome type	x	
Species composition	x	
Albedo	x	x
LAI	x	x
fAPAR	x	x
Fractional vegetation cover	x	x
Leaf chlorophyll content	x	x
Leaf water content		x
Leaf dry matter content		x
Leaf temperature	x	x
Soil temperature	x	x
Soil moisture	x	x

Table 2.1: *List of variables that can be derived from remote sensing observations and used to control process models in forcing or assimilation mode.*

The top-down approach consists of inverting atmospheric transport models against observations of atmospheric carbon dioxide concentrations to retrieve the spatial distribution of sources and sinks (Figure 2.9). These so-called 'inverse methods' are used extensively worldwide and take advantage of networks of flux and concentration measurements performed from high towers or sometimes from aircraft. They provide rather robust estimates of the spatially integrated carbon flux on time scales of seasons to years over global to sub-continental scales. However, published attempts to recover monthly fluxes at sub-continental scales from flask data have highlighted dramatic disagreements regarding the spatial structure of the sources and sinks (Rayner et al., 1999; Kaminski et al., 1999; Peylin et al., 1999; Bousquet et al., 2000). Inter-comparison experiments at the global scale have shown that leading models reproduce the available surface marine data when they are distant from local terrestrial sources or sinks, but disagree over the continents and, obviously, when the amount and quality of observational data are insufficient to constrain the model (Law et al., 1996; Denning et al., 1999). The effectiveness of inverse methods is thus currently limited to the coarser spatial resolutions over terrestrial surfaces for two main reasons:

- **Density of atmospheric CO_2 measurements.** The current network of atmospheric observing stations is very sparse and the stations are generally far from major landmasses. Specifically, the very dynamic longitudinal transport structure is not well resolved by this network.

- **Limitations of the atmospheric transport model.** Significant uncertainties in the estimation of regional fluxes arise from the necessary approximations or

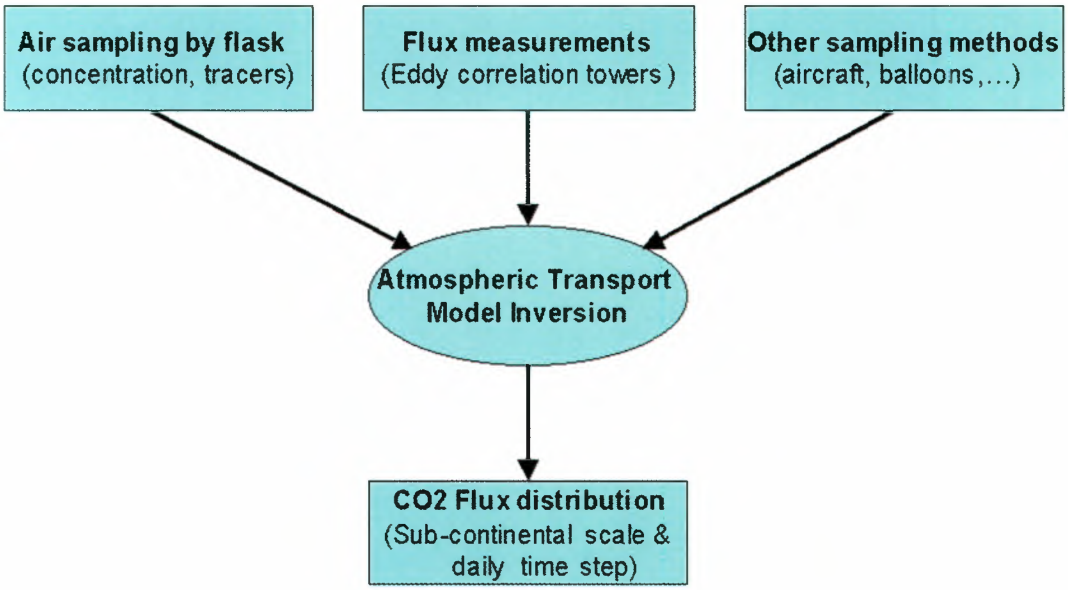

Figure 2.9: *Schematic of the top-down approach: inversion of transport models against CO_2 flux and concentration measurements.*

parameterisations in the atmospheric transport model, or the limitations of the mathematical approaches used in the inversion.

Although quite efficient for the description of the distribution of sources and sinks on very coarse spatial and long temporal scales, these inverse methods do not provide specific information on the mechanisms responsible for the retrieved fluxes. They thus have no predictive power to describe the long-term evolution of carbon fluxes under prescribed climatic constraints and human activity scenarios.

The bottom-up approach 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 2.10 shows some of the important variables as well as the data flows involved in this approach.

This bottom-up approach provides flux estimates at the resolution of the input data, which may be rather high compared to the previous top-down approach. It allows direct use of satellite observations to characterise 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. On the other hand, significant differences in model responses have been observed for identical prescribed initial and boundary conditions (Figure 2.11).

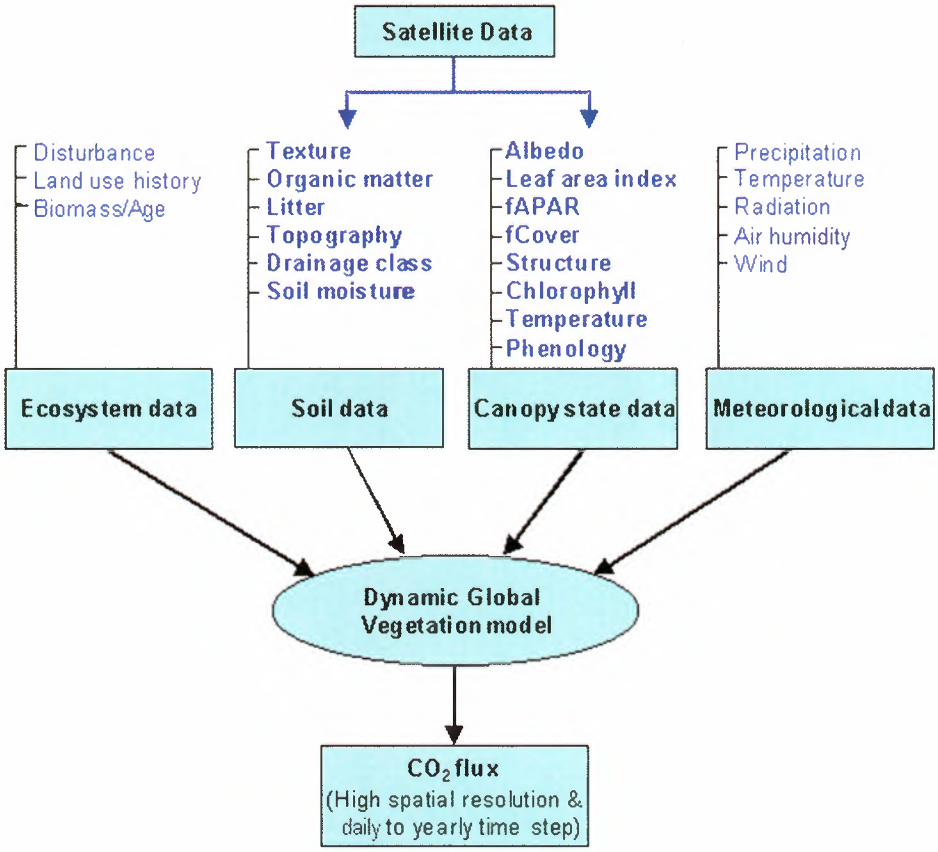

Figure 2.10: *Schematic of the bottom-up approach and associated model and data flows.*

As hinted above, this bottom-up approach is suitable for describing in great detail the processes occurring in the environment and to exploit satellite remote sensing data at the full resolution of the sensors. ***The main scientific question is then to assess to what extent findings derived at the local scale are representative of larger areas, i.e. what are the tools and methods to be used to scale up to the regional and global scales. This issue is at the core of the SPECTRA mission.***

2.6 Local Processes and Global Models: Spatial Heterogeneity and Scaling

2.6.1 How Global Models Describe Heterogeneous Terrestrial Vegetation

Spatial heterogeneity is a defining feature that distinguishes terrestrial surfaces from the oceans and the atmosphere. Reliable and accurate fluxes of carbon, water and energy are difficult to estimate at the regional to global scale because of the heterogeneity of the landscapes.

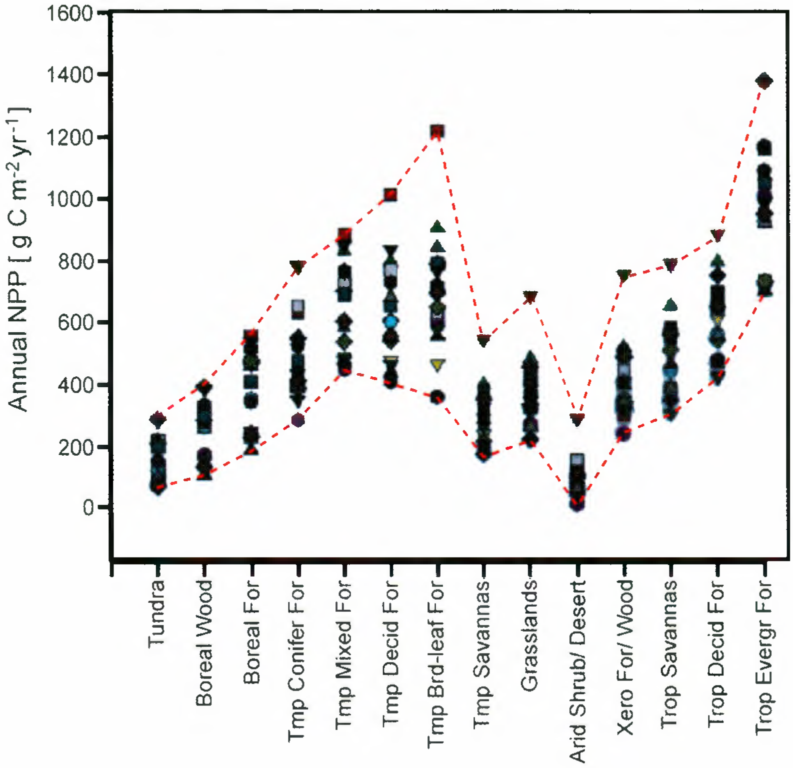

Figure 2.11: *Results from the comparison of the annual net primary productivity generated by 16 different Dynamic Global Vegetation Models (DGVM) for a range of biomes (after Cramer et al., 1999).*

Recent literature demonstrates that forecasts of the long-term evolution of climate depend quantitatively and qualitatively on how the response of terrestrial vegetation is parameterised. For example, Cox et al. (2000) demonstrated that plausible assumptions on the ratio of photosynthesis to respiration lead to substantially different evolutions of the global climate in response to increased CO_2 concentration in the atmosphere. Similarly, Claussen (1997) showed that different representations of biosphere processes may or may not lead to re-growth of vegetation in the Sahara in response to long-term climate trends.

From the point of view of modelling, we may distinguish two main approaches to representing land-atmosphere interactions in global models:

- 'Frozen biosphere': A map of global biomes (e.g. Figure 2.12) is used to determine the abundance of each land cover type for all model grid boxes. The exchanges of energy, water and carbon within each grid box are computed using a Land Surface Model (LSM; e.g. Figure 2.13). The properties of each biome are time-independent and are specified, typically in tabular form. This approach may be extended to use time-dependent biome properties, specified in an off-line database.

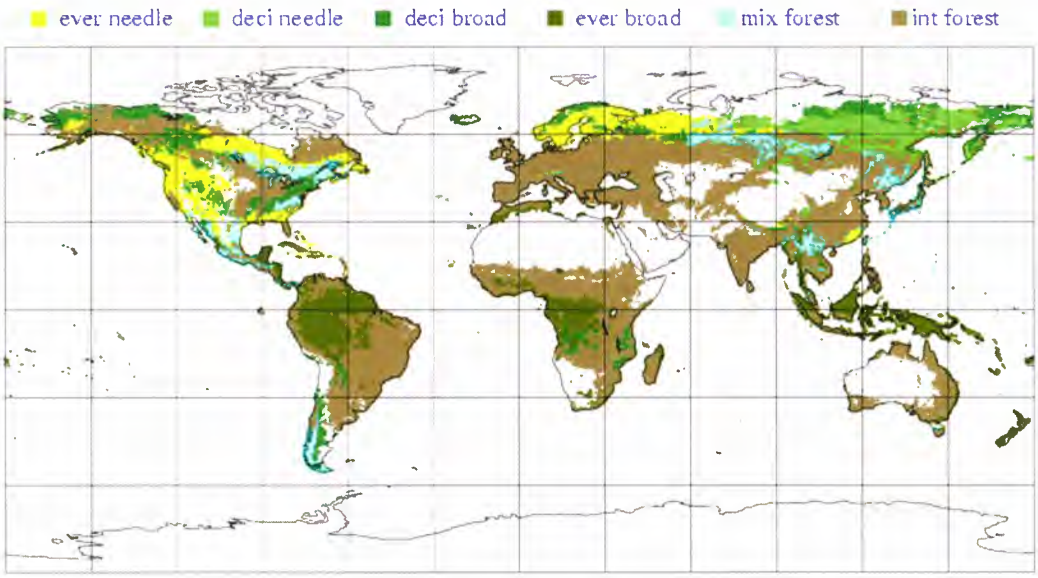

Figure 2.12: *Map of tall vegetation types currently used by the global ECMWF NWP model to parameterise the exchanges of energy, water and carbon between the terrestrial biosphere and the atmosphere. Legend: ever = evergreen, deci = deciduous, needle = needleleaf forest, broad = broadleaf forest, mix = mixed, int = interrupted (Courtesy: ECMWF).*

- 'Interactive biosphere': The LSMs in this category are far more complex than for models in the previous category. Some of them only describe photosynthesis and respiration, while others characterise the state of the biomes in great detail, including species composition and its evolution in response to climate forcing.

Documenting the state and evolution of terrestrial ecosystems involves describing a rather wide range of complex processes operating at the local scale. On the other hand, the LSMs implemented in global Earth System Models relate to entire regions, rather than samples of truly homogeneous biomes characterised by well defined, observable biosphere properties. While all relevant processes may be included in a model of the type depicted in Figure 2.13, such models lump the underlying heterogeneity and non-linearity of terrestrial biosphere processes into parameterisations at the scale of a model grid, say 100 km.

The implications of this modelling approach become evident when comparing the true complexity of heterogeneous landscapes (e.g. Figure 2.14) with a map of any of the properties as represented in most global models. Indeed, any one of these landscapes, no matter how heterogeneous or complex, is represented by a small set of properties that are kept constant over the entire area of 100 km x 100 km, as depicted in Figure 2.16a. Distributed models of terrestrial landscapes (e.g. Figure 2.15) are more accurate in describing heterogeneous landscapes and the mechanisms determining their functioning, and are the subject of intense on-going research.

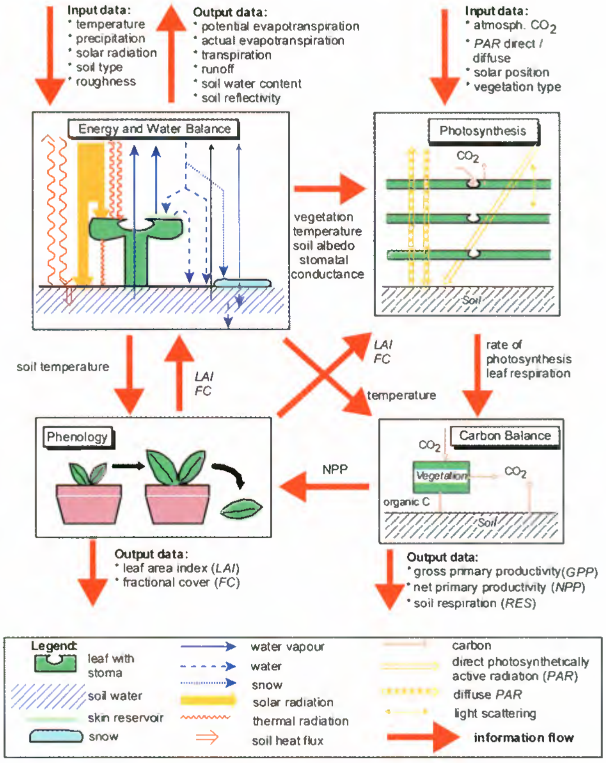

Figure: 2.13: *Variables and processes determining the response of terrestrial vegetation to environmental forcing in Land Surface Models (Knorr and Heimann, 2001).*

There is a clear knowledge gap between what is known empirically through local measurements and the idealisations contained in the parameterisations used in global models. ***A robust and scientifically sound strategy to fill this gap will require a focussed experimental and modelling plan covering an ensemble of regions, representative of all relevant terrestrial biomes, and the development of suitable parameterisations for each one of them. The SPECTRA mission is designed to directly address this issue.***

To meet this challenge, it will be necessary to study in detail the functioning of terrestrial vegetation over areas as large as the size of a grid box in global models. This will provide a solid basis for grid-box scale parameterisations of biosphere processes. We can distinguish three steps in this process:

- Observations of the terrestrial biosphere are collected at a spatial resolution sufficient to capture its heterogeneity (Figure 2.14).

- A detailed, distributed model of the region is constructed in a way that preserves the spatial organisation of the observed landscape (Figure 2.15) while permitting the estimation of overall quantities over the entire region covered by the distributed model.

Figure 2.14: *This ASTER-derived image, re-projected on a DEM, captures the heterogeneity of complex terrestrial landscapes as observed with a modern high resolution sensor over complex terrestrial landscapes: 3-D View of a region in Costa Rica (Image Credit: NASA/JPL/NIMA/UGS, http://earthobservatory.nasa.gov/ Newsroom/NewImages/images.php3?img_id=5029).*

- A simplified representation of the heterogeneity of the landscape within a model grid box (Figure 2.16) is developed for use in global models. State-of-the-art global models are evolving towards incorporating heterogeneity in two ways: either taking into account sub-grid variability of land cover, i.e. the so-called tiling or mosaic approach, where each tile interacts independently with the atmosphere (Figure 2.16a), or by distinguishing tall and low vegetation types (Figure 2.16b) within the entire grid box.

The next stage in this process of building up our understanding of terrestrial vegetation over a range of scales is to determine the relevant properties of these biomes at a spatial resolution sufficient to capture heterogeneity. This can be done by combining observations at high spatial resolution with data assimilation and modelling at the regional scale.

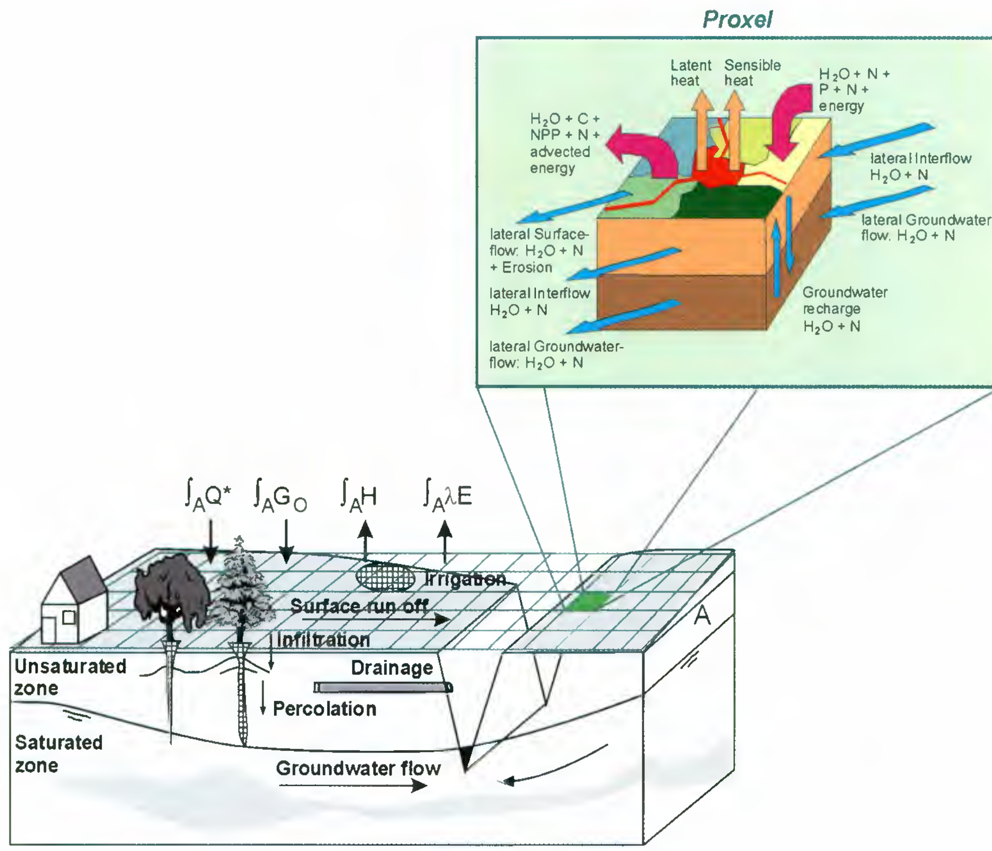

Figure 2.15: *Schematic structure of a distributed ecosystem model designed to take into account the spatial organisation of terrestrial vegetation and of the processes that determine the response of the biome to climate.*

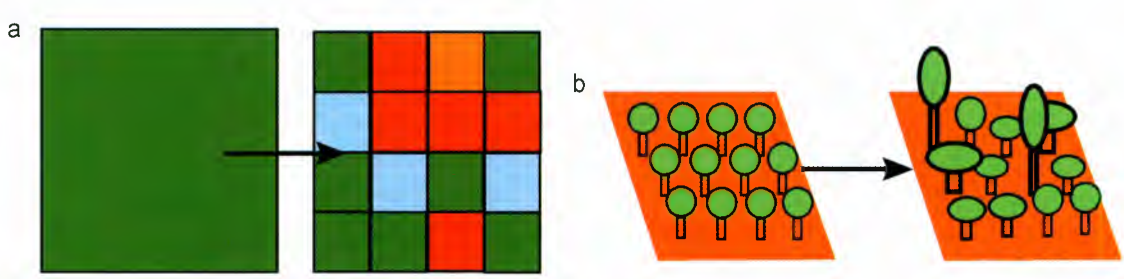

Figure 2.16: *Schematic of the way global models capture the heterogeneity of terrestrial vegetation. The land surface parameterisation implemented at ECMWF permits to distinguish multiple types of land covers within each GCM grid box (a, small squares), including low and tall vegetation types (b, see also Figure 2.12). (Courtesy of B.J.J.M. Van den Hurk).*

2.6.2 From Local to Global Scales

It is common practice to define the spatial scales of biosphere processes as follows:

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 (agriculture, deforestation, reforestation, afforestation, fires, etc.). When observed at the local scale, a landscape appears, such as that in Figure 2.14. ***The SPECTRA mission should resolve the local scale explicitly.***

The regional scale (10-100 km) is defined here as the typical scale of variability of a biome. At this scale, topography may play a dominant role on the transfer and storage of water with strong implications on vegetation functioning. Realistic models (Figure 2.15) can, however, be implemented to take into account the heterogeneity of variables and processes. This is also a useful scale to document the long-term evolution of spatial gradients, due to past disturbances, or to derive parameterisations for the DGVMs. Observations at this scale will also directly contribute to meeting the national reporting requirements of international conventions such as the Kyoto Protocol. For these reasons, ***the SPECTRA mission should provide observations over regions of the size of 10 to 100 km.*** The SPECTRA mission will help develop robust, detailed Dynamic Global 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, as illustrated in Figure 2.12. 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 into a homogeneous tile and disaggregating a model grid-box into several tiles (Figure 2.16a). In one case, tall and low vegetation types are treated separately (Figure 2.16b). The heterogeneity of the land surfaces is then taken into account by associating biome-specific parameterisations with a global biome distribution map (e.g. Figure 2.12). The SPECTRA mission will contribute indirectly to advances at this scale (for instance in closing the carbon cycle) through the improved parameterisations that are expected to be generated as a result of detailed studies on the regional scale. ***The SPECTRA mission should provide useful data for an ensemble of regions representative of the range of biomes and conditions encountered on Earth.***

2.7 Scientific Justification

Scaling up, i.e. the process of generating information at coarser scales than those at which it is originally derived, must have a solid modelling and observational basis. It will thus be essential to acquire low spatial resolution data, as is currently done with large swath optical sensors (e.g., NOAA/AVHRR, VEGETATION, MODIS, MISR, SeaWiFS, MERIS, POLDER, GLI), as well as high spatial resolution data with instruments such as SPECTRA. The most critical advance in this respect will be to scale up the information derived locally to the regional scale, which corresponds to the intrinsic resolution of global models.

The contribution of SPECTRA to the strategy developed recently is illustrated in Figures 2.17 and 2.18. For a selection of regions representing the various biomes, observational data generated through field studies and the SPECTRA mission will be used in conjunction with appropriate models to produce accurate environmental information at the regional scale (Figure 2.17).

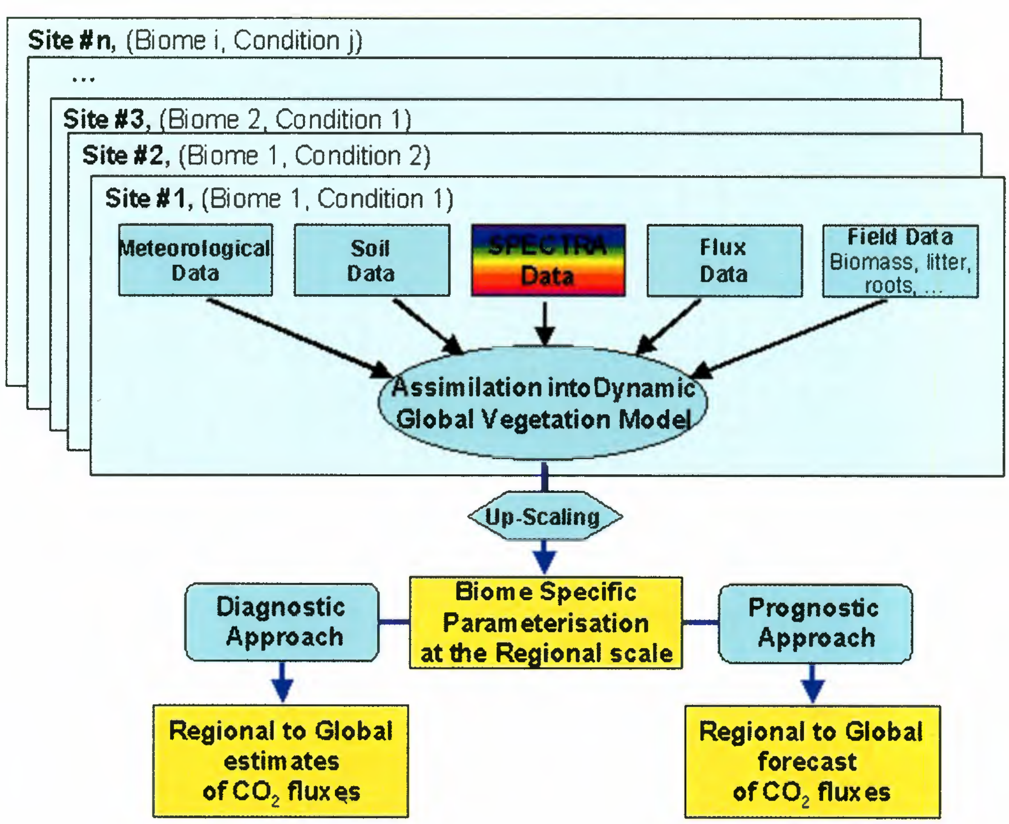

Figure 2.17: *The approach proposed to describe the terrestrial component of the carbon cycle using SPECTRA data.*

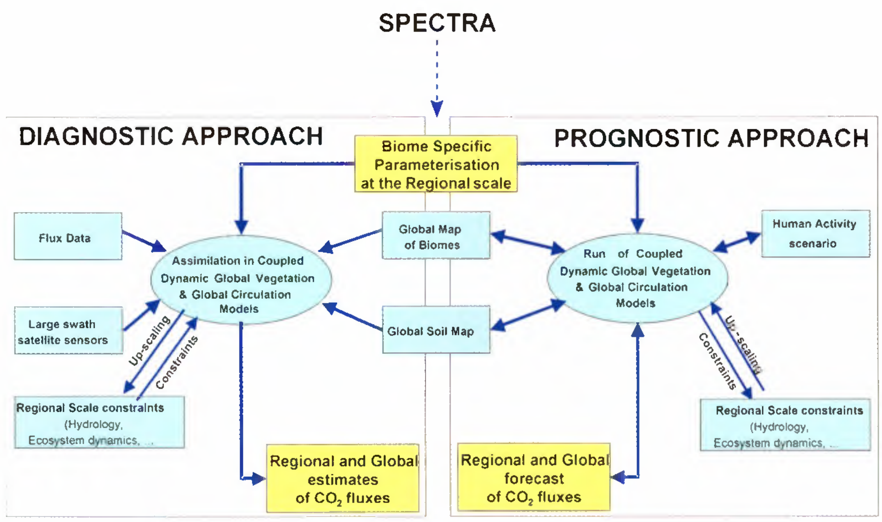

Figure 2.18: *The diagnostic and prognostic approaches used to estimate CO_2 fluxes at regional to global scales.*

This scaling up therefore relies on a two-step strategy, where field observations provide detailed *in-situ* measurements to document the processes at work. Satellite data, such as would be generated by the SPECTRA mission, are then used in conjunction with appropriate models to develop improved biome-specific parameterisations at the regional scale. The latter are exploited by global models to generate estimates at that scale, using a suitable distribution of biomes, following either of two different approaches (Figure 2.18), depending on the time scale considered:

- ***Diagnostic approach.*** Improved parameterisation in combination with large swath, low spatial resolution satellite data will improve model accuracy and stability. The exploitation of large swath satellite data will be mainly based on the development of assimilation techniques (e.g. Viovy et al., 2001).

- ***Prognostic approach.*** In this case, model stability is essential to obtain reliable assessments of long-term trends. The SPECTRA mission will contribute directly to the development of robust parameterisations of biosphere processes. Longer time series of observations may provide additional supporting evidence, for instance with respect to the important coupling between vegetation dynamics and climate, as reported by Cox et al. (2000).

2.8 Delta of the Mission

SPECTRA will fill a specific gap in the current science of the terrestrial biosphere, namely how to describe processes at the regional scale with sufficient accuracy using simple models adapted to the low spatial resolution of global Earth System Models (Figure 2.19).

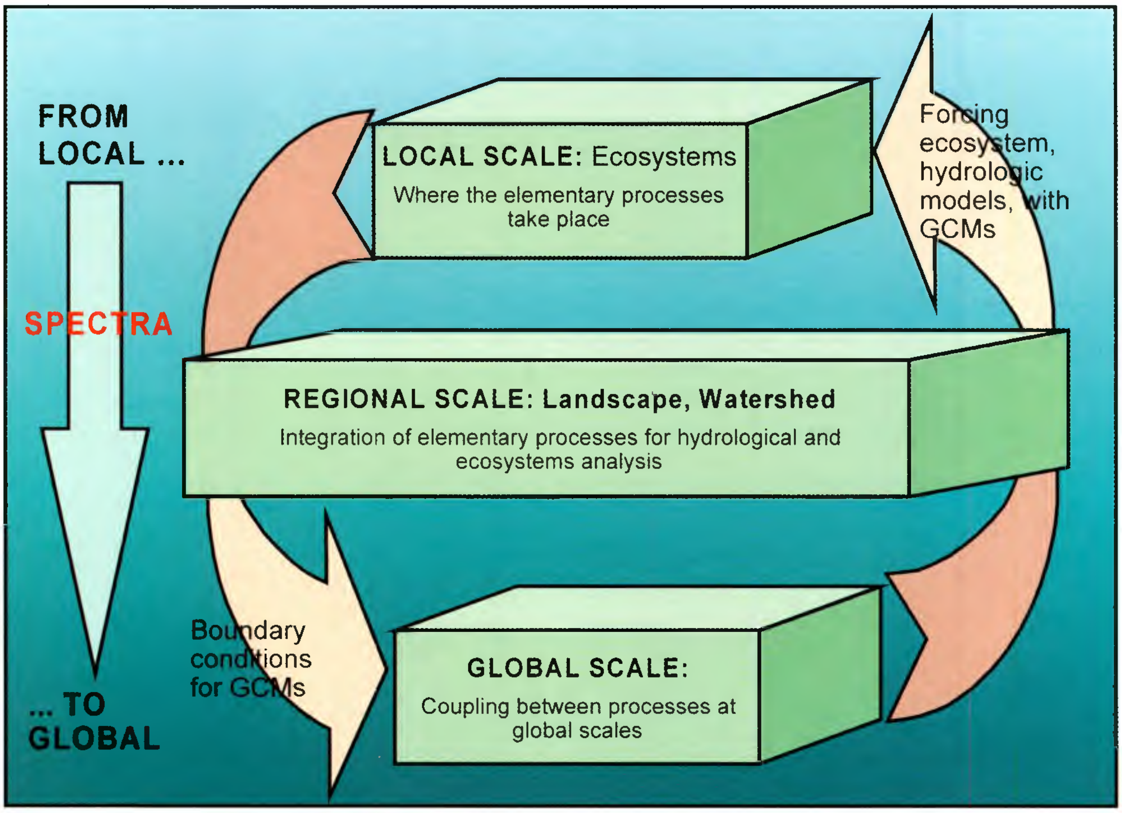

Figure 2.19: *Conceptual approach to link the local with the regional and global scales. The mission of SPECTRA is to build the knowledge, the data and the models to link the local with the regional scale.*

This will be achieved by performing detailed studies linking the local with the regional scale by means of detailed, spatially distributed models (Figure 2.17). These studies will integrate *in-situ* observations with SPECTRA data for all biomes.

This approach requires accurate data to constrain the detailed regional models, and here SPECTRA makes a unique contribution: the SPECTRA observations of vegetation amount and condition will provide an unprecedented wealth and accuracy of information by simultaneously exploiting the spectral and angular dimensions of radiance data.

In summary, the SPECTRA mission will provide a unique opportunity to observe in great detail a set of regions representative of the various terrestrial biomes. These observations will have a spatial resolution high enough to document the heterogeneity of the landscape, and be compatible with the scale of field measurements. They will cover areas large enough to encompass regions representative of typical biomes, and these regions will be distributed globally. The observations collected by SPECTRA, together with the measurements on the ground and the models available, will permit the derivation of new or better parameterisations to represent variables and processes critical for documenting the state and evolution of the vegetation cover. These parameterisations, in turn, will be used in Dynamic Global Vegetation Models and other global models, for instance those addressing the carbon cycle, to generate global estimates of quantities such as fluxes of carbon, water, and energy at the land surface. It is also foreseen that some models may be able to assimilate directly the observations or the dynamic products generated by SPECTRA. These developments will significantly enhance the performance of global models, as well as our ability to take full advantage of lower resolutions sensors.

3 Research Objectives

3.1 General Research Goal

To advance our current understanding of the response of terrestrial ecosystems to environmental forcing and human induced stresses, including forest management, cropping practices, deforestation and biomass burning, observable changes in the type and amount of terrestrial vegetation need to be related to known changes in specific forcing factors, such as precipitation, temperature and anthropogenic emissions of pollutants or land use changes. A detailed knowledge of the relevant processes at the local scale is not sufficient. Effective policymaking must be based on accurate, reliable information on the regional, national or global scale. Yet, as was discussed in the previous chapter, the complexity of this endeavour (linked to the heterogeneity of the landscape and the difficulties in scaling up from local measurements) is precisely the major stumbling block in this respect. This scientific challenge must be addressed through a coordinated combination of modelling studies and observational programmes. The SPECTRA mission is uniquely designed to contribute to the solution of this problem.

The scientific goal of the SPECTRA mission is to describe, understand and model the role of terrestrial vegetation in the global carbon cycle and its response to climate variability under the increasing pressure of human activity.

3.2 Specific Research Objective

The mission will provide detailed observations of key properties of terrestrial biomes that can be assimilated by dynamic vegetation models to describe the accumulation and transformation of biomass in response to environmental forcing at the regional scale. The scientific deliverables of the mission, i.e. the amount and state of vegetation, will be generated from an analysis of field and remote sensing data with process models. This will lead to robust, biome-specific parameterisations and, therefore, a better quantification of the terrestrial carbon cycle.

Recent process modelling studies of land biomes tend to assimilate radiometric observations directly instead of biogeophysical variables (e.g. Asner, 1998). This requires integration of ecosystems 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 which is high enough to capture homogeneous samples of land cover types.

Our understanding of the processes determining the response of vegetation to environmental forcing has been developed through observation and modelling of individual ecosystems with severe limitations in the observable spatial scale. This led to the development of many different parameterisations for the same biome. To build a global science of terrestrial ecosystems, IGBP and WCRP have coordinated initiatives to establish networks of sites and experiments dedicated to specific ecosystem processes.

The SPECTRA mission thus aims at:

- providing precise measurements of vegetation amount and conditions with a spatial resolution sufficient to characterise individual vegetation types
- learning how to incorporate heterogeneity of terrestrial vegetation into global Earth system models, and
- linking regional scale observations and models with global Earth system models.

SPECTRA is designed to bridge the gap between observations at the local scale and parameterisations at the regional scale. These advances will lead to a more robust description of global biosphere processes.

3.3 Approach

3.3.1 Sampling Terrestrial Biomes: An Ensemble of Representative Regions

The combined requirements of capturing both the heterogeneity and dynamics of terrestrial vegetation, and of performing detailed process studies, rule out global coverage of observations and modelling analyses. The mission capitalises on and significantly enhances the research efforts of the international community at the local, regional and global scales, by providing the observational evidence that will help describe the heterogeneity of the landscapes and design new or better parameterisations of local processes for use in global models. Figure 3.1 summarises the integration of on-going studies of the carbon cycle at different scales that could profitably use observations such as those that will be generated by SPECTRA.

SPECTRA will collect time series of detailed observations over regions centred on sites typical of the various biomes, for an ensemble of representative regions, as shown in Figure 3.1. Detailed models (see Figure 2.15) exist or will be constructed for each region, as part of explicit collaborations between scientific teams running field experiments and groups involved in remote sensing data analysis. The SPECTRA observations will be used to retrieve detailed maps of vegetation properties and for data assimilation, using coupled process- and radiative transfer models. A conceptual scheme of the data assimilation approach at the regional scale is shown in Figure 3.2. This procedure is applied for each individual remote sensing measurement (image element or pixel) to generate regional maps of vegetation properties.

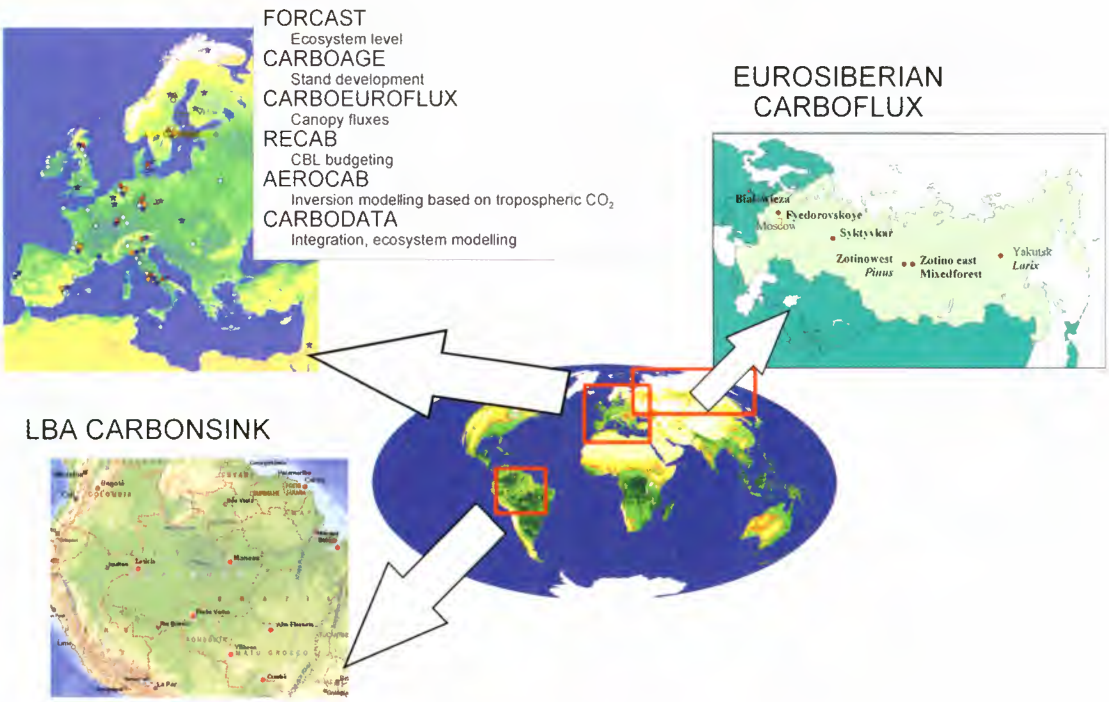

Figure 3.1: *Global network of research sites to improve current knowledge of the terrestrial component of the global carbon cycle; acronyms refer to specific research projects (Courtesy of A.J. Dolman).*

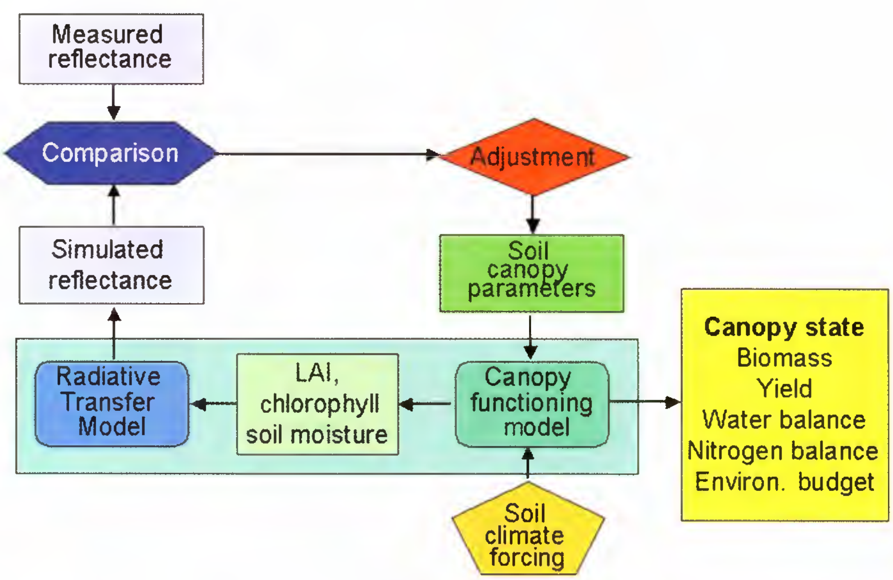

Figure 3.2: *Conceptual scheme of how SPECTRA observations will be assimilated at the regional scale.*

3.3.2 Parameterising Processes at the Regional Scale with SPECTRA Observations

The following three examples (a to c) exemplify how detailed observations such as those that will be generated by SPECTRA can be used by models in assimilation mode to generate spatially correct distributions of relevant variables. In each case, regional estimates of these variables can be derived explicitly from such findings.

a) <u>Assimilation of spectro-directional radiometric observations to improve estimates of NPP</u>

Bach et al. (2000) used the PROMET model, driven by meteorological, soil, nutrient and agronomic data, to estimate grain yield in an agricultural region of the Upper Rhine basin in Germany. A second experiment was carried out, in which Landsat Thematic Mapper data were assimilated throughout the growing season. The two panels of Figure 3.3 show the spatial distribution of yield estimates generated with both procedures. The differences between these panels underscore the impact of assimilation of remote sensing data on the procedure.

Comparison of these results with field measurements showed that the assimilation of spectro-directional radiometric observations significantly improved the accuracy of the product.

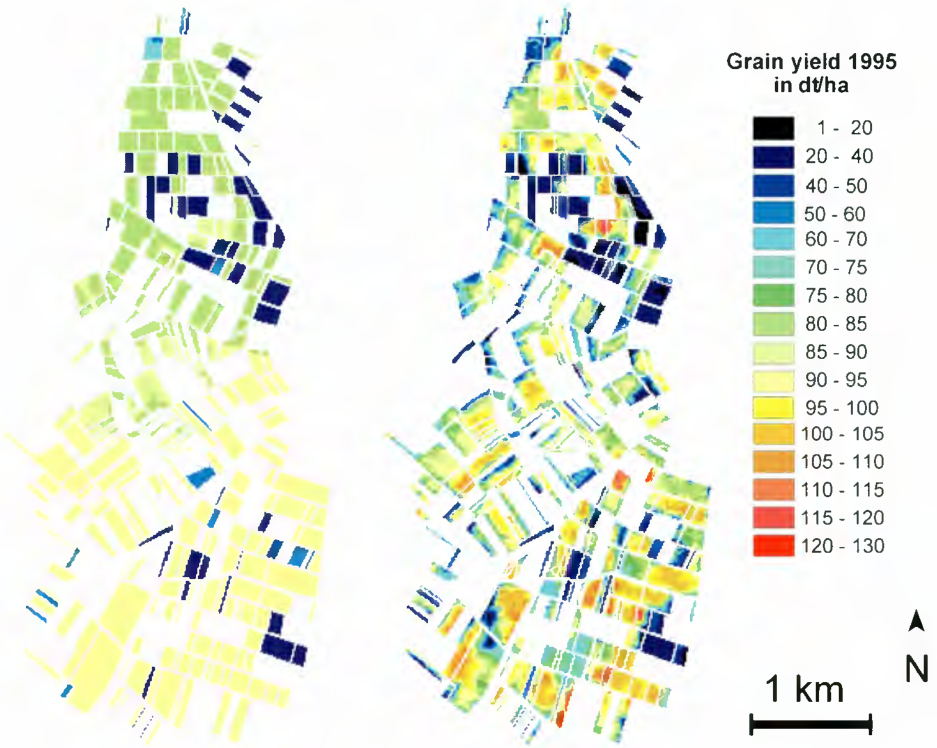

Figure 3.3: *Grain yield estimated without (left) and with (right) assimilation of spectro-directional radiometric observations (after Bach et al., 2000).*

b) Assimilation of spectro-directional radiometric observations to parameterise soil respiration

Knorr and Heimann (2001) used AVHRR data to improve the parameterisation of NPP and Carbon Release (*SR*) in a Dynamic Global Vegetation Model (see also Knorr and Heimann, 1995). The carbon release was parameterised as:

$$SR = \alpha \cdot Q_{10}{}^{T/10} \tag{3.1}$$

where α is a water stress factor, related to canopy conductance for gas exchanges, and Q_{10} is an empirical variable determining the rate of change of carbon release, which is quite sensitive to the value of Q_{10}, and so is NEP. In the data assimilation experiment, Light Use Efficiency and Q_{10} were chosen as free variables. Results obtained by assimilating spectro-directional radiometric data (AVHRR in this case) improved the estimates of Q_{10} (Figure 3.4; Kaminski et al., 2001).

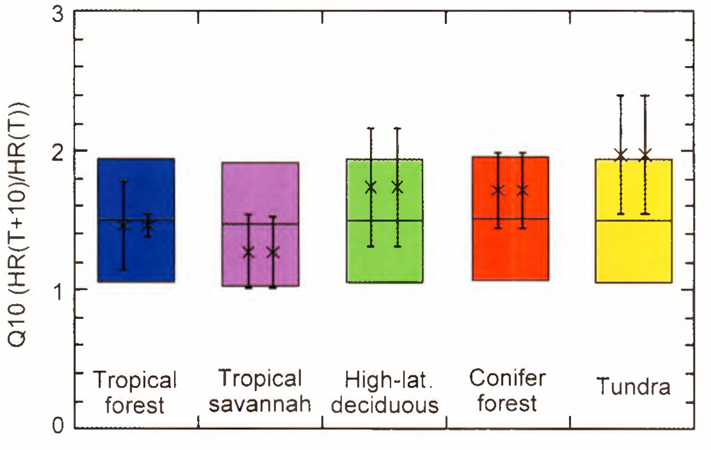

Figure 3.4: *Estimated Q_{10} values for different biomes. Coloured boxes show a priori uncertainties, while vertical bars indicate the estimated errors after the assimilation of spectro-directional observations from space (after Kaminsi et al., 2001).*

c) Assimilation of foliage and soil temperature to improve heat transfer modelling

The parameterisation of the sensible heat exchange is a weak point in global Earth System Models. Van den Hurk et al. (2001) assimilated observations 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. Data assimilation was performed for two regions at 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 (Figure 3.5).

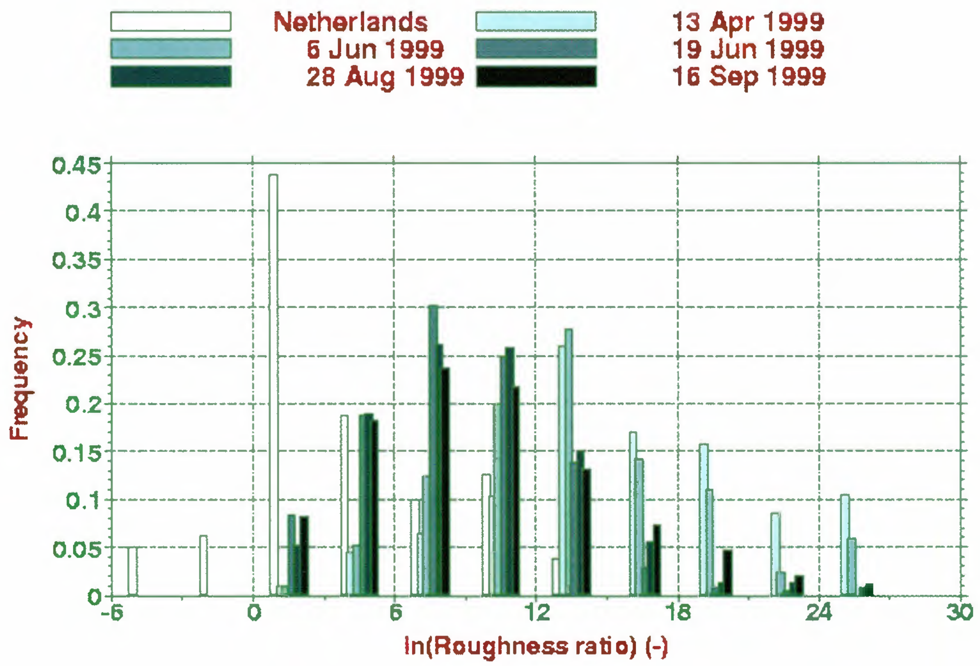

Figure 3.5: *Roughness length for sensible heat transport: spatial distribution at different times of the year obtained by assimilating observations of foliage and soil temperature in an advanced Earth system model (Van den Hurk et al., 2001).*

The performance of this data assimilation procedure was evaluated by comparing forecasts with observations of air temperature and humidity. These results lead to improvements in the accuracy of the forecasts, as well as in regional scale estimates of the roughness length for sensible heat transport.

In summary, these examples show that:

a) current distributed models of biosphere processes can assimilate spectro-directional radiometric observations to improve estimates of NPP;

b) data assimilation does provide access to complex variables, such as soil respiration at the regional scales, not easily observed with local measurements;

c) multi-angular thermal infrared observations provide new opportunities to improve a critical element of global land-atmosphere models: the parameterisation of sensible heat transfer.

3.3.3 Data Assimilation at the Global Scale

Once the approach outlined above has been applied to an ensemble of representative regions, the biome-specific models may be linked together to build a global data assimilation system such as the one proposed by Knorr and Heimann (2001) and presented in Figure 3.6. The SPECTRA mission will be particularly relevant to achieving this objective, as it will provide substantial empirical evidence on which to build the improved parameterisations needed by the global models to carry out continental or global estimations of the stocks and fluxes of carbon.

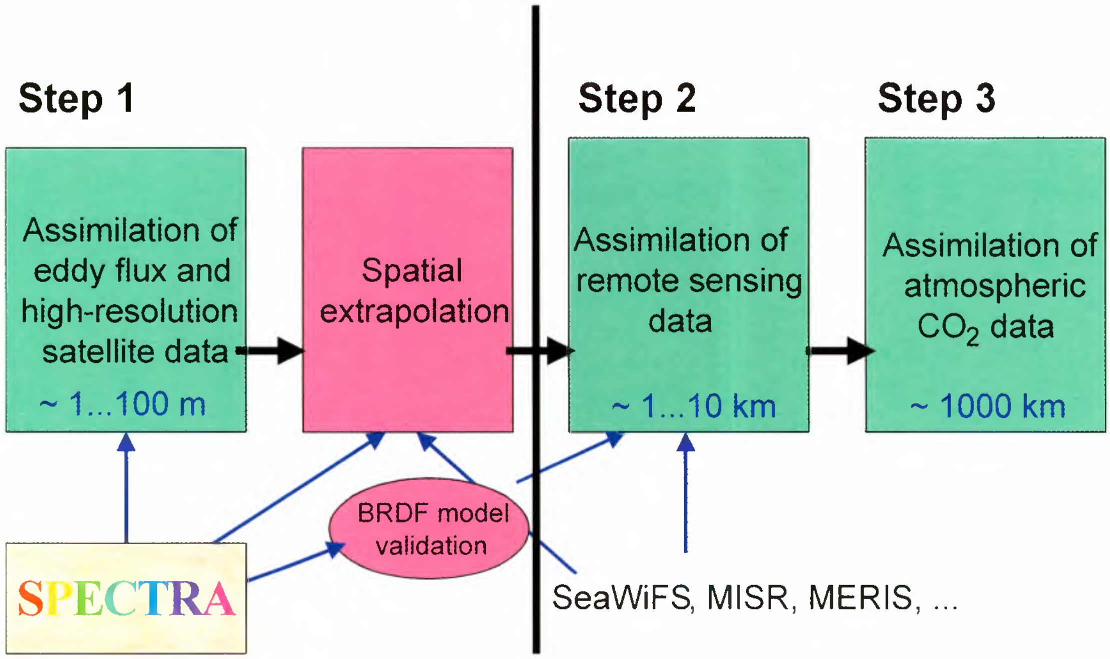

Figure 3.6: *Conceptual scheme of multi-scale modelling and data assimilation system (after Knorr and Heimann, 2001): SPECTRA observations are used at the regional scale to improve models of each region.*

Such a global data assimilation system will be based on the biome-specific parameterisations established with the support of the SPECTRA mission (Figure 3.7). These parameterisations will be constructed by first modelling each region in detail (see Figure 2.15) and then learning how to simplify such detailed and complex models through observations and data assimilation.

3.4 Observational Objective of the Mission

SPECTRA will provide accurate, quantitative measurements suitable for assessing the state and amount of vegetation, its role in the terrestrial carbon cycle, as well as its response to climate variability on seasonal to inter-annual time scales, for a set of regions representative of relevant biomes. Specifically, the mission will be aimed at deriving the following variables from the remote sensing observations:

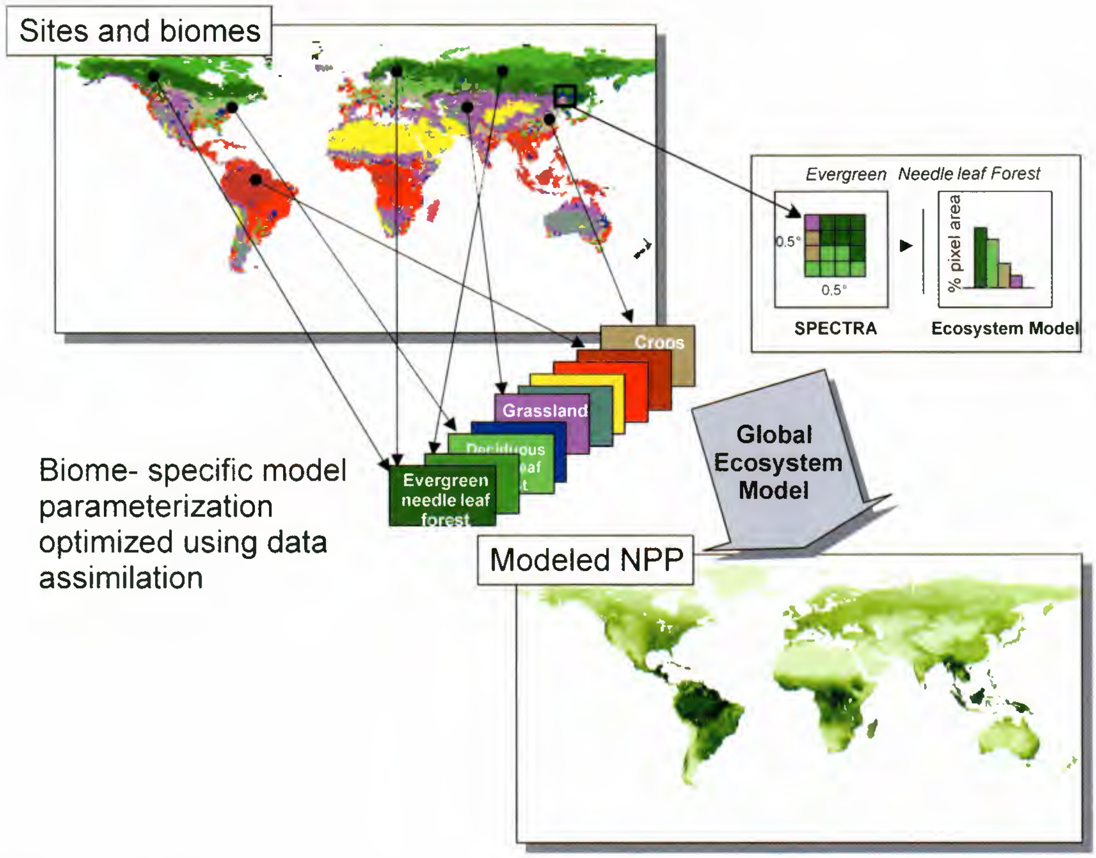

Figure 3.7: *Overview of the proposed approach for integrating regional, biome-specific models with global models of the terrestrial biosphere (Courtesy of G. Churkina).*

- fractional vegetation cover
- fraction Absorbed Photosynthetically Active Radiation (fAPAR)
- albedo
- leaf Area Index (LAI)
- leaf chlorophyll content
- leaf water content
- leaf dry matter content
- foliage temperature
- soil temperature
- fractional cover of living and dead biomass.

In addition, the mission will help design or improve algorithms for exploiting observations at lower spatial resolution and limited spectral and directional sampling. These algorithms will be developed using the observations provided by the mission as a benchmark over the selected regions.

We expect that the high accuracy for vegetation properties, achievable with the SPECTRA mission, will enhance significantly the scientific and practical benefits of the multi-scale data assimilation approach described in this report.

Each SPECTRA data set will cover a sufficiently large sample of a terrestrial biome. We have indicated this spatial scale as 'regional'. For the purpose of this report, 'sufficiently large' means 50 km x 50 km.

4 Observational Requirements

4.1 Introduction and Observational Approach

The specific observational objective of the SPECTRA mission is to provide accurate values of the vegetation properties described in Section 3.4.

Strictly speaking, none of these variables can be measured directly from space. On the other hand, the architecture of terrestrial vegetation and the biochemical composition of canopy elements determine an information-rich radiance field in the optical region of the spectrum (Figure 4.1), in the sense that the observed spectro-directional radiance field carries information closely related to the required key vegetation properties. This chapter describes (a) how the reflected or emitted radiation field carries information on the properties of terrestrial environments, (b) how these relations can be inverted to retrieve information on the environment from remote sensing data, and (c) the proposed observational strategy required to meet the objectives of the SPECTRA mission.

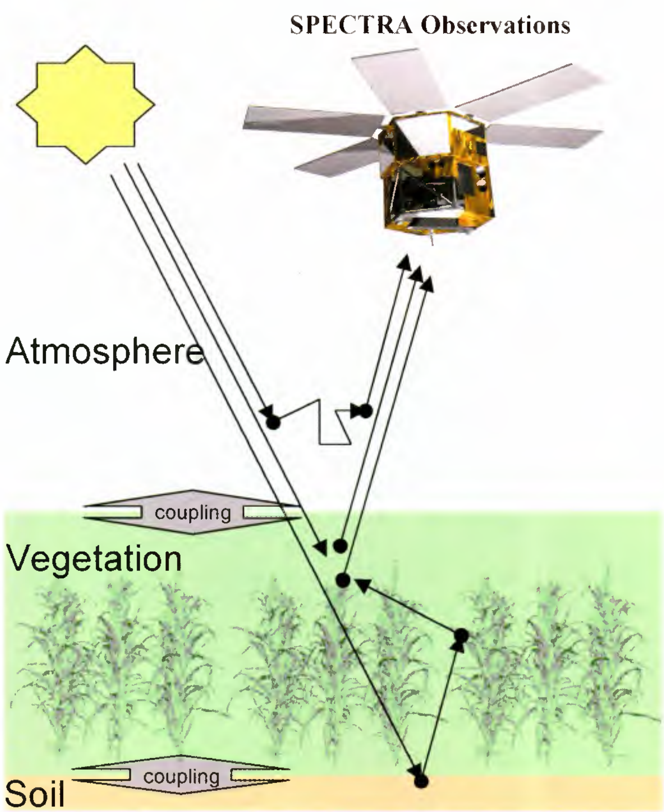

Figure 4.1: Schematic of the interactions of the radiation with the soil-vegetation-atmosphere, showing the coupling between the radiative transfers of each of these components.

Since land surfaces are always observed through the atmosphere, and since these two geophysical media interact significantly, the proper interpretation of radiation measurements made in space must take full account of the many scattering and absorption processes that take place in this complex geophysical system. The optimal way to take account of this complexity is to make full use of the directional and spectral signatures of this coupled system, by acquiring directional spectral measurements and to analyse those with suitable models (Martonchik et al., 1998b).

Some geophysical variables, 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.

Figure 4.2 is a schematic of the various models needed to simulate the spectral and directional signatures of terrestrial biomes at the resolution effectively implemented in typical Earth Observation sensors. These models must take into account, for instance,

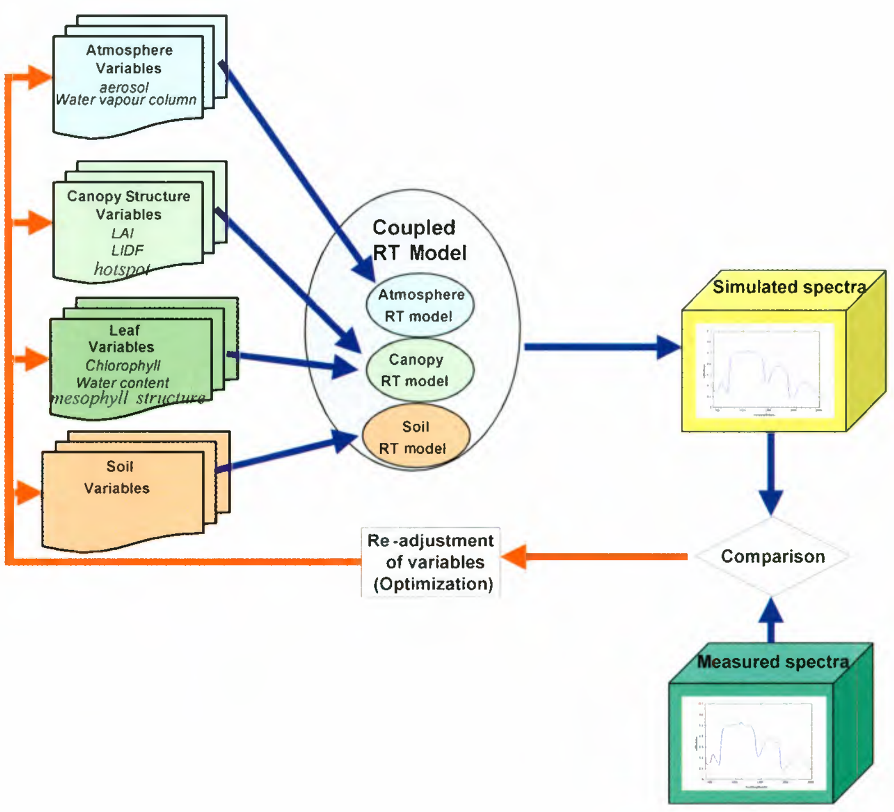

Figure 4.2: *Integrated modelling of radiative transfer in the soil, vegetation, atmosphere continuum; LIDF = Leaf Inclination Distribution Function; other variables explained in the text.*

the architecture of plant canopies, the properties of the plant elements and of the soil, as well as the relevant atmospheric processes.

Such comprehensive models can be used in several ways, particularly to develop algorithms to retrieve the variables listed above. The following sections provide multiple examples of how spectro-directional radiometric observations have to be analysed to retrieve the information of interest, using state of the art models.

4.2 Retrieval of Vegetation Properties from Space: Science Background

All remote-sensing 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 for a series of reasons:

- The angular position of the Sun relative to the target being observed changes continuously with time during the day, and from day to day throughout the season.

- The measurements for each location of a given scene are obtained from a particular direction that also changes from pixel to pixel within the image (and from day to day throughout the season when multiple data sets are acquired).

- All land surfaces are anisotropic:
  - In the solar domain, the vegetation reflects solar light differently in different directions (early work on this topic is summarised by Gates, 1980; later contributions include Ross, 1981 and Verstraete, 1987) because the scattering elements (leaves, branches, soil, etc.) are themselves anisotropic (e.g. Brakke et al., 1989; Brakke, 1994), and because of their spatial arrangement (e.g., Verstraete et al., 1990; Pinty et al., 1990). The contrast between the optical properties of leaves and background, as well as the distribution of illuminated and shadowed parts are the main drivers of the anisotropy. A series of models, either purely descriptive (e.g. Rahman et al., 1993a and 1993b) or based on radiative transfer modelling (e.g. Gobron et al., 1997) have been proposed. An extensive model intercomparison exercise has been conducted to review some of the models available in the literature, and results were recently published by Pinty et al. (2001).
  - In the thermal-infrared domain, the directional variation of emitted fluxes (described by the so-called brightness temperature) is mainly determined by the distribution of temperature and emissivity between the elements of the canopy, and by the structure of the vegetation (see Balick et al., 1987; Kimes and Kirchner, 1983). Similar to the solar domain, the distribution of shadowed and illuminated parts, as well as the amount of soil and vegetation observable from a particular direction, are the main drivers of the anisotropy models that have been developed to describe the directional variations in this spectral

domain (e.g. Norman and Chen, 1990; Otterman, 1990; Smith and Goltz, 1995; François et al., 1997).

- The anisotropy of the surface can be visualised by creating an image that colour codes the directional instead of the spectral signature (see, for example, Figure 4.3).

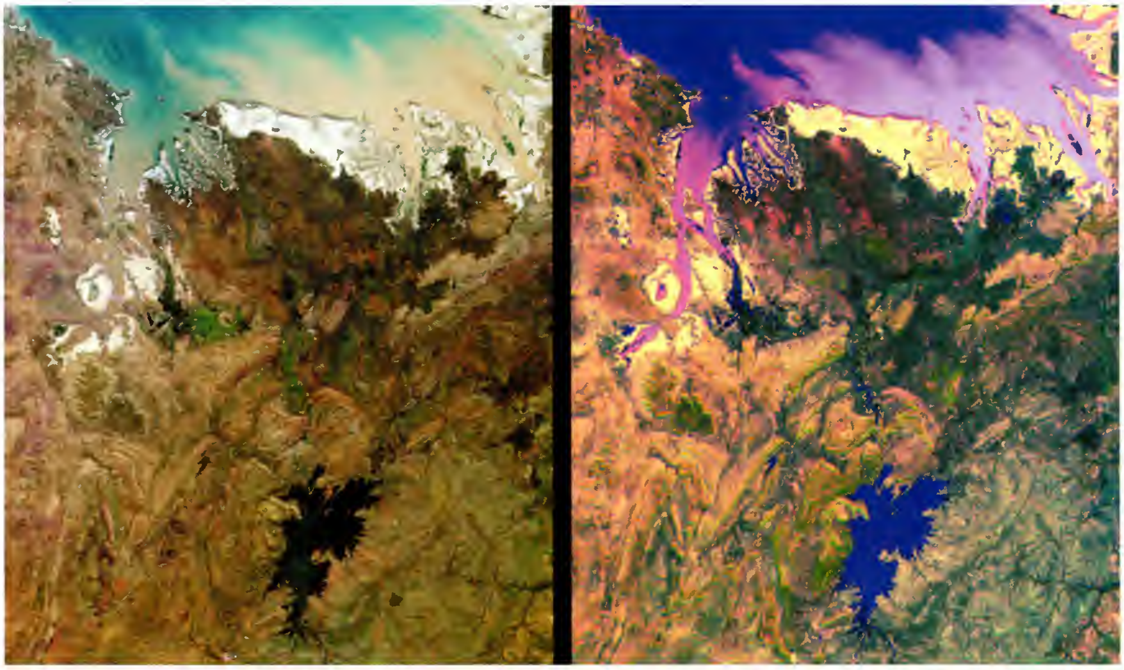

Figure 4.3: *MISR images of tropical Northern Australia acquired on 1 June, 2000 (Terra orbit 2413) during the long dry season. Left: colour composite of vertical (nadir) camera blue, green, and red band data. Right: multi-angle composite of red band data only from the cameras viewing 60 degrees aft, 60 degrees forward, and nadir. Colour and contrast have been enhanced to highlight subtle details. In the left image, colour variations indicate how different parts of the scene reflect light differently at blue, green, and red wavelengths; in the right image colour variations show how these same scene elements reflect light differently at different angles of view. (Image Credit: NASA/GSFC/JPL, MISR Science Team, http://www-misr.jpl.nasa.gov/gallery/galhistory/2000_jul_19.html).*

- The anisotropy of surfaces is spectrally variable. For instance, the hot spot feature in vegetation canopies is more sharply defined in the visible than in the near-infrared spectral domain because multiple scattering tends to smooth out the directional signature; the same applies to specular reflectance, if it is present in the scene. More generally, the spectral dependence of the anisotropy has been extensively documented through observations made with POLDER, MISR and HYMAP.

- At the same time, the overlying atmosphere also exhibits significant spectral and anisotropic signatures. The absorption bands due to water vapour or CO_2 are well known. Figure 4.4 shows the anisotropy of the atmosphere over a homogeneously dark oceanic surface, from different observation zenith angles, as can be observed with the MISR instrument.

Figure 4.4: *A multi-angle view of the Canary Islands in a dust storm, on 29 February 2000. At left is a true-colour image taken by the MISR instrument on NASA's Terra platform. This image was captured by the camera looking at a 70.5° angle to the surface, ahead of the spacecraft. The middle image was taken by the downward-looking (nadir) camera, and the right image is from the aftward-looking 70.5° camera. The images are reproduced using the same radiometric scale, so that variations in brightness, colour, and contrast represent true variations in surface and atmospheric reflectance with angle. Windblown dust from the Sahara Desert is apparent in all three images, and is much brighter in the oblique views. The images are about 400 km wide, with a spatial resolution of about 1.1 km. North is toward the top. (Image Credit: NASA/GSFC/JPL, MISR Science Team, http://www-misr.jpl.nasa.gov/gallery/galhistory/2000_jun_07.html)*

- Last but not least, the surface and the atmosphere are radiatively coupled in complex ways through multiple scattering.

In summary, 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 (Figure 4.5). *Thus, all Earth observations acquired in space are intrinsically dependent on the particular geometry of illumination and observation at the time of the measurement.* A detailed analysis of the anisotropy of these measurements will yield additional information on the structure and properties of the observed system. In addition, the angular signature can be exploited to improve the accuracy and reliability of products derived by other means, for instance by providing a much better characterisation of the overlaying atmosphere.

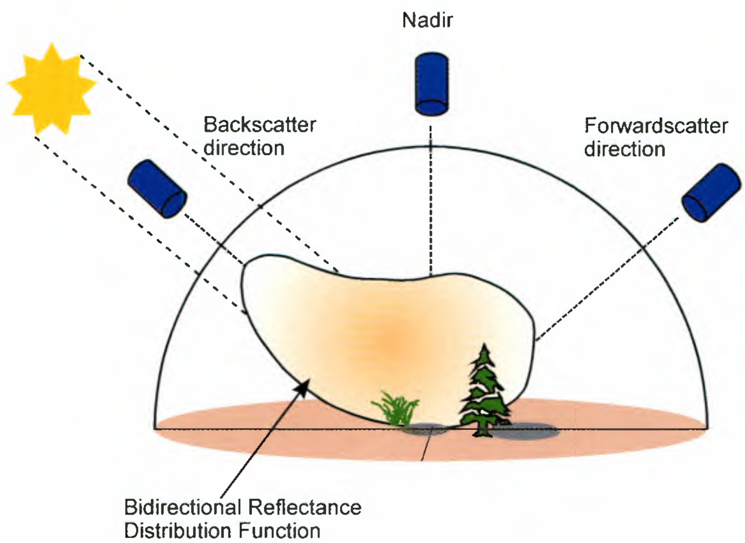

Figure 4.5: *Schematic of the directionality of the reflectance as a function of the zenith angles of illumination and observation in the principal plane (the one that contains the source of illumination and the local vertical at the site being observed). The bulge visible in this diagram (known as the hot spot) is meant to represent the increased reflectance of the vegetation in the direction of illumination, compared to other directions. The emission of thermal radiation is also directionally variable, but the physical processes involved are different (after Irons et al., 1991).*

In the spectral range where radiative forcing is provided by the Sun (300 nm – 3000 nm), matter absorbs radiation at specific wavelengths, which correspond to the electronic, rotational and vibrational bands of the molecules constituting the materials. Hence, measurements that can result in a characterisation of these absorption bands provide, in principle, information on the chemical composition of these materials. This is the fundamental principle of spectroscopy. Radiation not absorbed in matter is generally scattered, i.e. its direction of propagation is altered by the presence of matter. Here again, the directional distribution of scattered radiation is peculiar to the nature and structure of matter, as was seen above.

The same physics applies to the biochemicals present in vegetation and soils. A synthesis of the literature (Figure 4.6) confirms that spectral reflectance measurements of 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 this relationship (Figure 4.7).

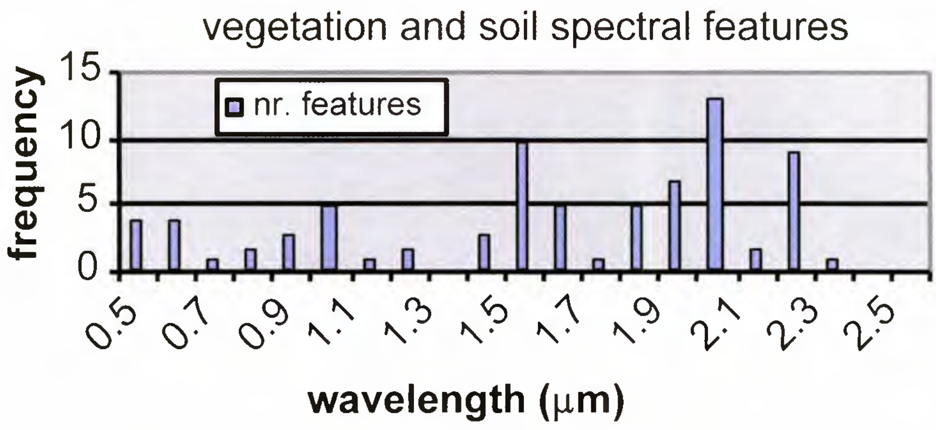

Figure 4.6: *Summary of an extensive literature search on significant spectral features of vegetation and soil (Menenti, 2001). The numbers of independent literature entries on individual absorption features associated with a specific soil or vegetation element, as a function of wavelength, are shown. Numbers of spectral features have been binned in 20 nm intervals.*

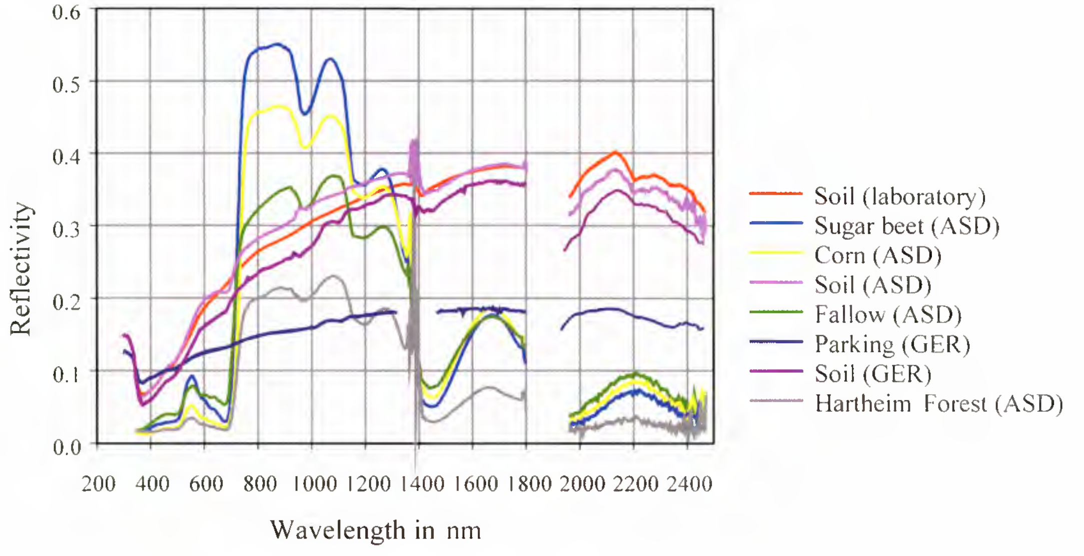

Figure 4.7: *Reflectance spectra for targets observed within a representative landscape comprised of arable land and forest in the Upper Rhine region of Germany. Field measurements were obtained with portable field spectrometers (manufactured by the ASD and GER companies) in July 1999. Adapted from Nerry et al. (2001).*

Over the past 20 years, a general focus on the characterisation of broad vegetation patterns over continents and the wide availability of instruments offering repeated observations, at coarse spatial resolution and in a few spectral bands only, have led to the belief that a limited set of spectral bands (in the range of 10 to 40 bands) would be sufficient to address most problems of interest (e.g. Price, 1990; Price, 1994; Price, 1997). However, recent advances with airborne spectroscopy have 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 radiometric resolution and the performance of that instrument have been extensively documented (Eastwood et al., 2000), and the dimensionality of the datasets was evaluated at around 60 dimensions on average. Separately, Asner and Lobell (2000) found that soils and vegetation could be accurately unmixed using spectral derivatives from about 30 channels in the region 2100-2400 nm. The current balance of evidence thus points to the usefulness and strong potential of contiguous spectral observations in specific regions of the spectrum.

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. As explained earlier, the acquisition of these measurements at multiple angles will permit one to distinguish between soil and canopy temperatures (Menenti et al., 2001), and thus retrieve further information on the structure of the environment. As will be seen later, 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 high-end portion of the atmospheric window ($\lambda > 10\ \mu m$). This choice simplifies significantly the analysis of spectral measurements in this spectral region.

4.3 Retrieval of Key Variables

4.3.1 Algorithm Development

Conceptually, 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 models and assumptions (Verstraete et al., 1996; Menenti et al., 2001). In any case, models provide a link between the radiometric data and the variables and processes controlling these observations (Figures 4.1 and 4.2). The desired information is retrieved by 'inverting' the model against the spectro-directional radiometric observations, whereby the values of the bio-geophysical variables that best account for these observations are deemed to accurately represent the state of the environment.

A large panoply of models has been proposed to interpret remote sensing data. They range from simple empirical or statistical relations that attempt to directly relate remote sensing measurements to an environmental variable of interest, to detailed models of radiation transfer in three dimensions. Correlations between observations in space and variables in the field can be established when both types of measurements take place at the same time for the same place. The advantage of this approach is that such a relationship, established locally, can easily be extended over a much larger area, thanks to the spatial coverage provided by the space sensor, and as long as that relationship holds. The drawbacks include the inability to explain why this relationship may exist and its limited applicability to other situations or time.

Physically based models of radiation transfer attempt to provide an explicit description of how solar or thermal radiation interact with the geophysical elements in the scene. The simplest models in this category, for instance, assume that the geophysical medium with which light interacts is homogeneous in the horizontal plane. Whenever these models are sufficiently detailed for the intended purpose, they also provide an economical solution in terms of computer resources. These one-dimensional vertical models may require typically from 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 as a linear combination of such simplified models is multiplied by 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), 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 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, including by Govaerts and Verstraete (1998), Knyazikhin et al. (1998), and Kimes et al. (2001).

The selection of an optimal model results from a compromise between the nature and accuracy of the desired information, the type and quality of measurements, and the allowable exploitation cost (Gobron et al., 2000). The implications of choosing a particular tool for data interpretation are illustrated in Table 4.1.

In summary, the nature and accuracy of the information retrieved from remote sensing depends strongly on the type of model used in the retrieval, and on the extent to which the observations constrain the selected model in the inversion process. Perhaps less intuitively, complex models often become so tied to the detailed description of a particular environment that their applicability to other situations is not guaranteed. From that point of view, a more generic one-dimensional model may describe the radiation transfer problem globally but at the cost of a poorer information content in particular situations. In any case, data of higher radiometric quality, acquired under a more extensive sampling scheme, should provide a better constraint on the model inversion process, and should thus lead to more accurate retrieval of vegetation properties.

Desired information	Input required	Interpretation tool	Output retrieved	Sources of errors
Presence of vegetation	Leaf spectral properties	NDVI[a]	Single numerical value to be correlated with the desired information	Atm, soil, aniso
	Previous + soil line	SAVI[b]		Atm, aniso
	Previous + atmosphere	GEMI[c]		Aniso
Quantitative vegetation attributes	Oriented point particles uniformly distributed	Inclusion of LAD and plate scattering model	Canopy properties such as leaf R_l and T_l, and LAD	Compacity and heterogeneity
	Oriented plates uniformly distributed	Inclusion of leaf size effects	Same as above + canopy height, leaf size, and number	Spatial heterogeneity
Land cover identification	Specification of radiative properties in 3D space	Inclusion of spatial distribution	Explicit scene	Validity of the representation of the scene

a: Normalized Difference Vegetation Index, Rouse et al. (1973).
b: Soil Adjusted Vegetation Index, Huete (1988).
c: Global Environment Monitoring Index, Pinty and Verstraete (1992).

Table 4.1: *Input, output, and sources of errors associated with a particular approach to satellite data interpretation (see text for details). 'Atm' and 'aniso' stand for atmospheric and anisotropic perturbing effects, respectively. LAD, R_l and T_l refer to the Leaf Angle Distribution function, and leaf reflectance and transmittance, respectively. (From Gobron et al., 2000).*

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

- optimisation methods are designed to iteratively identify the best match between observations and model predictions.

- Artificial Neural Networks (ANNs) are algorithms that can be 'trained' to recognise patterns or estimate a value; and

- Look-Up Table (LUTs) approaches are 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.

4.3.2 Optimal Spectro-Directional Sampling: Case-Studies

The following study examples demonstrate how environmental information is actually extracted from remote sensing data, and how this knowledge can be exploited to define the optimal observational strategy.

Hemispherical reflectance

The goal of this study (Vogt et al., 2000) was to determine the qualitative and quantitative impact, on the estimation of the albedo and the BRF field, of:

- a variable number and position of angular observations (for two given solar zenith angles),

- the assumption of a Lambertian surface reflectance, as well as

- the error associated with the selection of a predefined BRF shape (e.g. Figure 4.8) in the case of a single observation from an arbitrary angular position.

The situations considered in the simulation study are listed in Table 4.2. For each situation, the Martonchik-modified Rahman-Pinty-Verstraete parametric model (MRPV; Engelsen et al., 1996) was used to simulate the BRF of each surface type by means of the three parameters ρ_0^M, b_M, and k. A 5% Gaussian-distributed noise was added to the simulated BRF.

To evaluate alternative angular sampling schemes, a limited number of BRFs were extracted from the noisy BRF matrix. In conjunction with the known solar position, they were used to invert the MRPV model to obtain the three model parameters (ρ_0^M, b_M, k). Applying the derived values of these model parameters in a forward mode permitted the reconstruction of the entire BRF field. The latter was integrated to estimate the 'noisy' albedo. This was compared to the true albedo, which is based on all 50 directions of observation. Results obtained (Figure 4.9) show how large errors can be when estimating hemispherical reflectance from a single angular measurement. At least five, well-distributed, angles are necessary to maintain errors within acceptable bounds.

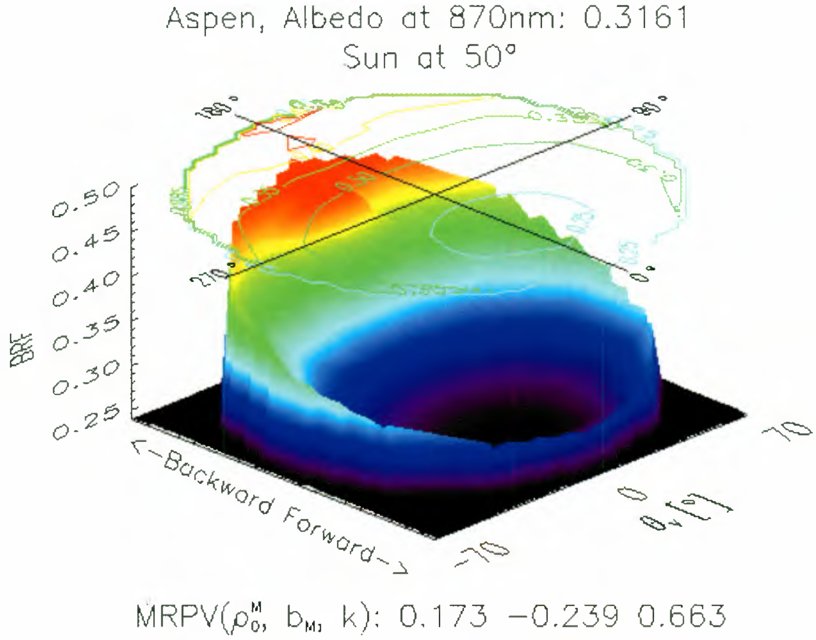

Figure 4.8: *Simulated near-infrared BRF field using the optimal MRPV model parameters retrieved from measured BRFs over an Aspen forest (after Deering et al., 1994). The MRPV parameter* ρ_0^M *describes the overall reflectance magnitude,* b_M *the forward/backward asymmetry, and k the steepness of the bowl shape of the BRF (Figure credit: P. Vogt).*

Observer zenith angle [°]	[0, 10, 20, 30, 40, 50, 60, 70]
Relative azimuth angle [°]	[0, 30, 60, 90, 120, 150, 180]
Solar zenith angle [°]	[20, 50]
Surface type	Aspen, Spruce, Pine, Tropical forest, Corn, Grassland, Hard wheat, Soil, Steppe
Wavelength [nm]	[670, 870]

Table 4.2: *Geophysical situations used in the study of the retrieval accuracy for hemispherical reflectance.*

Leaf Area Index, Chlorophyll content, fractional cover and fAPAR

The objective of this study (Weiss et al., 2001) was to assess the feasibility of estimating canopy biophysical variables from remote sensing data observed at the top of the canopy in several wavebands within the visible to near-infrared spectral domain. The variables considered were the leaf area index, leaf chlorophyll content, the fraction

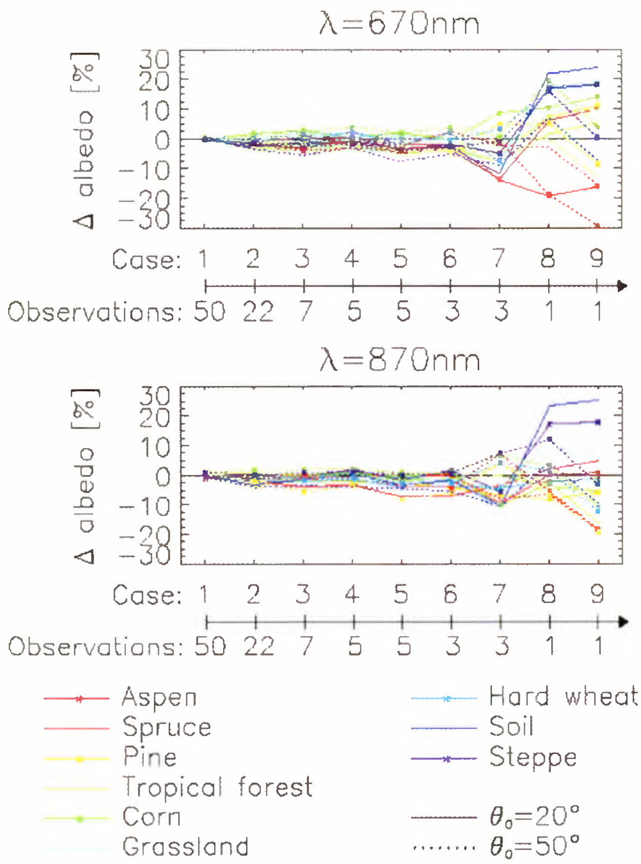

Figure 4.9: *Relative error in albedo retrieval accuracy for various observation scenarios over several surface types, for two solar positions* θ_0 = *20°, 50°, and in the RED (top) and NIR (bottom). These results are based on an analysis of noisy data, as described in the text (Courtesy: P. Vogt).*

of photosynthetically active radiation absorbed by the canopy and the vegetation cover fraction. The optimal spectral sampling to estimate the variables considered was investigated. The impact of spatial heterogeneity on the retrieval performances, the effect of the model assumptions used to generate the look-up table and the effect of radiometric noise were evaluated. These results were discussed in view of the definition of the SPECTRA mission and the selection of the best measurement configuration for accurate estimation of canopy characteristics. The study was restricted to top of canopy reflectance data, so it did not address the problem of atmospheric corrections. Furthermore, for simplicity, the Sun position was set at a 45° zenith angle, and no diffuse radiation was considered.

A number of canopy realisations were generated, thanks to the SAIL model (Verhoef, 1984, 1985 and 1998), by randomly drawing each radiative transfer model input variable from given statistical distribution laws. The input variables were assumed to be independent because no information was available about their possible covariance.

The distribution law of each variable was selected so that the probability density was set to be proportional to the sensitivity of the reflectance to the variable considered. One important consequence of this process is that low LAI, leaf chlorophyll content C_{ab}, leaf water content C_w and hot spot values were more densely sampled. A total of 280 000 simulations were generated using Monte-Carlo drawings.

A reference data set (called 3D) was generated by applying the PARCINOPY ray tracing code (Chelle, 1997) to a 3D model of maize canopy architecture (España et al., 1998). Eighteen cases, corresponding to six development stages and variations in leaf chlorophyll content and soil type were considered for the two test data sets. Since the ray tracing technique used for the 3D test case required large computer resources, a limited set of wavebands was simulated in the visible and near-infrared domains, which are the more relevant spectral regions for LAI, leaf chlorophyll content, canopy structure and fAPAR estimation (Asner, 1998). Nine spectral bands of 10 nm width each were considered, centred at 500, 562, 630, 692, 710, 740, 795, 845, and 882 nm. In this first step, only nadir viewing was considered. The evaluation of the best band selection was performed over this reference data set and under the conditions described above.

Results (Figure 4.10) 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 optimal estimation of the secondary variables fAPAR and fCover required fewer bands (4 and 5, respectively) than the primary variables LAI and C_{ab} (6 for each). The RMSE value differences computed over the biophysical variables of interest between the best and the poorest band selection demonstrated that the choice of the bands was obviously important, particularly for the first bands selected. 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. This results in the need to sample the spectral interval of relevance in a contiguous fashion.

A similar retrieval problem was studied by Verhoef (2001) who evaluated the simultaneous retrieval of process and radiometric variables by means of classical model inversion methods. Canopy reflectance in the red edge was modelled (Figure 4.11) for a series of combinations of LAI and leaf chlorophyll concentration. The LAI varies according to the series 0, 0.25, 0.5, 1, 2, 4 and 8. Chlorophyll concentration is given by the series 15, 20, 25, ..., 60, 70 and 80 $\mu g\ cm^{-2}$. The spectral bands represent the wavelength range from 670 to 800 nm at 10 nm intervals. The variables retrieved, using a procedure similar to the one schematically described in Figure 4.2, included soil brightness, soil spectral slope, canopy LAI, average leaf slope, bimodality parameter of the leaf inclination distribution function (LIDF), canopy hot spot parameter, leaf chlorophyll concentration, leaf mesophyll parameter, visibility at sea level in km, aerosol Ångström coefficient and aerosol single scattering albedo. Thus, 11 variables were retrieved using 14 bands evenly spaced across a limited spectral range.

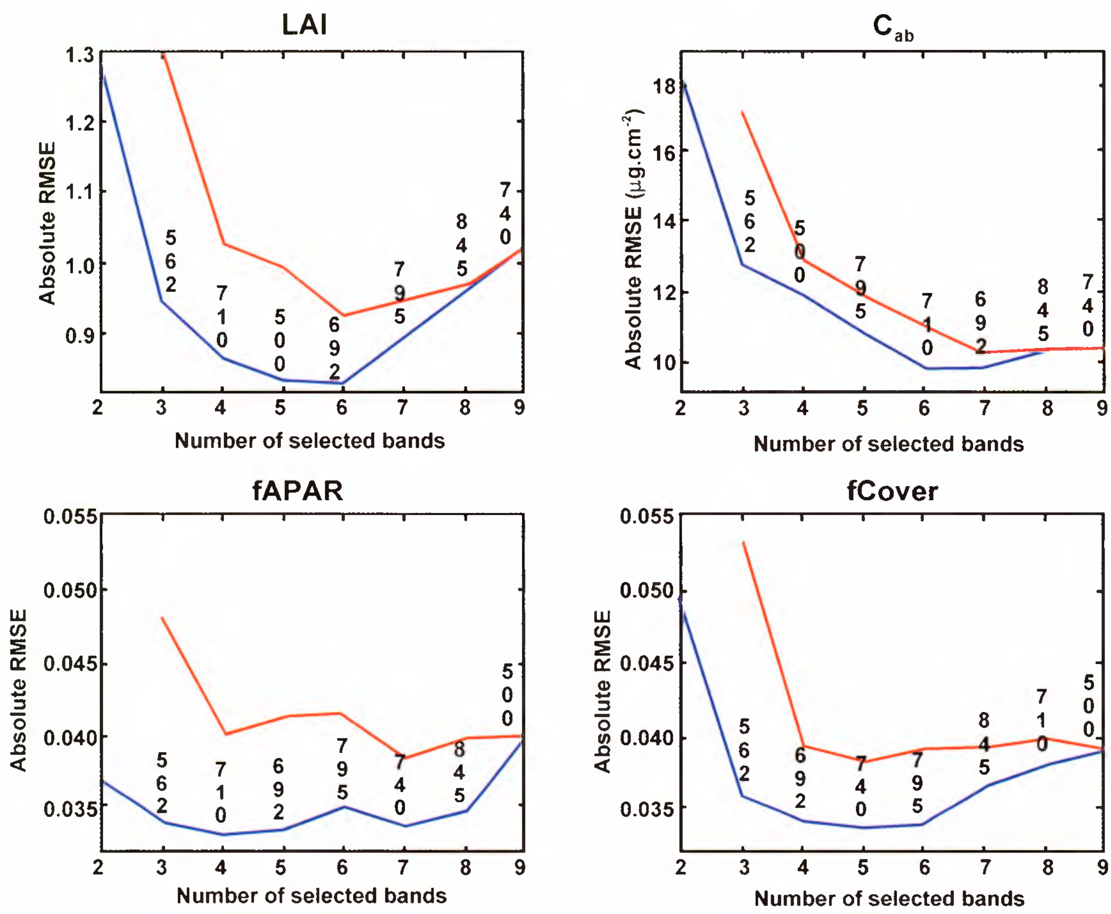

Figure 4.10: *Accuracy of LAI, Cab, fAPAR, and fCover estimates as a function of the number of bands selected). The curves start by just using red (630 nm) and near infrared (882 nm) bands. Then additional bands are added. The blue line corresponds to the best band combination (the wavelength (nm) of the best n^{th} band is indicated above the curve, and should be read top-down) and the red line to the worst combination (after Weiss et al., 2000).*

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 numerous and precise to identify which spectrum is actually observed. Taking into account the additional ambiguities introduced by other variables affecting spectral reflectance, we may expect that better measurements, i.e. at higher spectral resolution and better radiometric accuracy, would lead to smaller errors on retrieved variables. As usual, the interpretation of observational data may lead to the identification of more than one possible solution. The acquisition of more detailed data (both spectrally and directionally, in the case of remote sensing) of increased radiometric quality constrains the inversion procedure better and thus leads to more

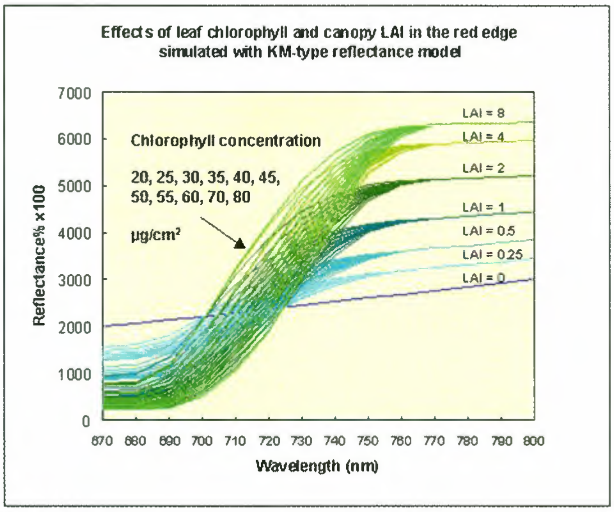

Figure 4.11: *Effects of leaf chlorophyll and LAI on canopy reflectance (multiplied by 10 000) in the red edge spectral region: each spectrum was simulated (see also Figure 4.2) for a given combination of* C_{ab} *and LAI as indicated; KM refers to Kubelka Munk (Verhoef, 1998; Verhoef, 2001).*

reliable results. Moreover, continuous spectra may provide new yet simple methods of determining vegetation properties. One example is the shift in the position of the intercept between the vegetation and the bare soil (LAI = 0) spectra. This position (see Figure 4.11) depends only on the chlorophyll content, so precise determination of the spectral position of the intercept provides an estimate of the chlorophyll content.

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 may prove useful in constraining the inversion procedure and ensuring the reliability of the results. In that sense a contiguous reflectance spectrum will limit the impact of errors on the accuracy and reliability of retrievals, as demonstrated by the following example.

Leaf water content

This geophysical variable can be retrieved by analysing specific spectral absorption bands of liquid water. 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) on the basis of both modelling and actual hyperspectral data.

The approach was similar to the one developed and applied by Verhoef (2001), but explored in an innovative way the use of measurements in the Short-Wave InfraRed (SWIR). A coupled soil, leaf/canopy, atmospheric model (see, for example, Figure 4.2) was directly inverted against continuous reflectance spectra at high spectral resolution, by taking into account all coupled absorptions and multiple scattering effects (inside the canopy and between the canopy and the soil). This approach was evaluated using AVIRIS and DAIS data sets collected in Barrax, Spain at different times.

Simulated reflectance spectra (Figure 4.12) were evaluated against AVIRIS data at different locations. Matching was excellent overall, but significant deviations were observed at some wavelengths. This highlighted the importance of using continuous reflectance spectra at high spectral resolution. These deviations would have a significant impact on retrieval if measurements were limited to a few spectral bands. The retrieval of leaf water content by inversion permits one to take advantage of significantly more complex spectral features (Figure 4.13) when the observational data are resolved enough to reveal them.

Soil composition

Absorption bands at the far end of the SWIR may be used to infer soil composition and condition, for example in relation to soil fertility. Leone and Menenti (2001) used field measurements of soil spectral reflectance at very high spectral resolution (Figure 4.14) to evaluate the impact of progressively lower spectral resolutions on the characterisation, and therefore on the inversion, of specific absorption bands. The actual measurements were smoothed using a filter of increasing width, from 15 nm (5 data points) to 90 nm (30 data points). The depth and the curvature of the absorption bands changed considerably, implying a significant impact on the retrieval.

Retrieval of foliage and soil surface component temperatures with multi-angular thermal infrared measurements

Multi-angular thermal infrared measurements provide access to the component temperatures of soil and foliage within heterogeneous land targets. Because of the heterogeneity in the architecture of vegetation canopies, the local balance of energy in the canopy space varies significantly. The combination of thermal heterogeneity and canopy architecture determines a significant angular change in emitted radiance. This directional signal may be used to explore the link between radiative and aerodynamic properties of terrestrial vegetation canopies. The relationship was exploited by Menenti et al. (2001) to estimate the component soil and foliage temperatures of different regions using the bi-angular TIR measurements obtained with ATSR-1 and ATSR-2. Notwithstanding the limitations of these observations, such as the difference in spatial

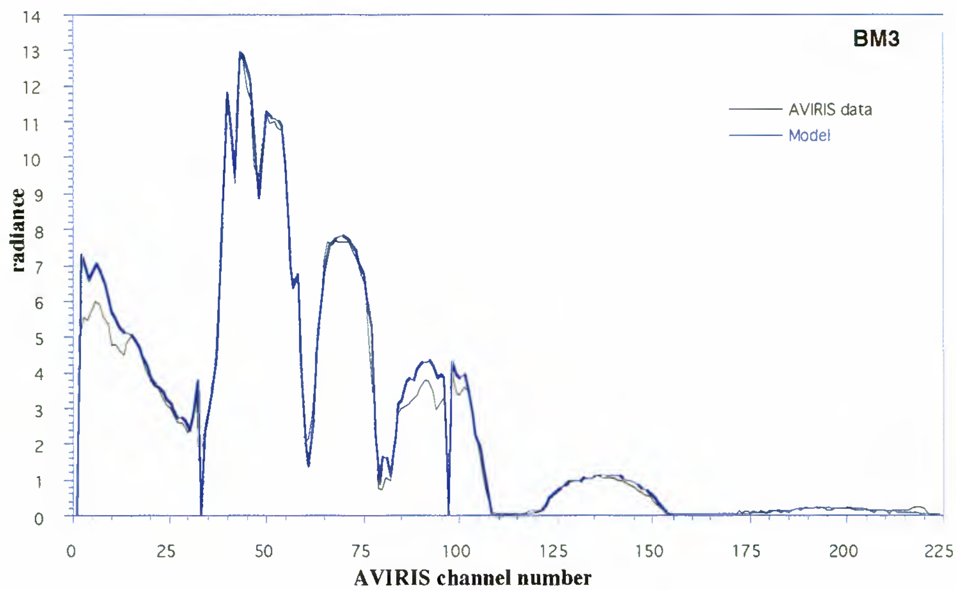

Figure 4.12: *Comparison between AVIRIS measured radiance data (mW cm^{-2} μm^{-1} sr^{-1}) and model calculations, for the cornfield BM3 in the Barrax area, Spain, observed on 15 July 1991 (Courtesy: J. Moreno).*

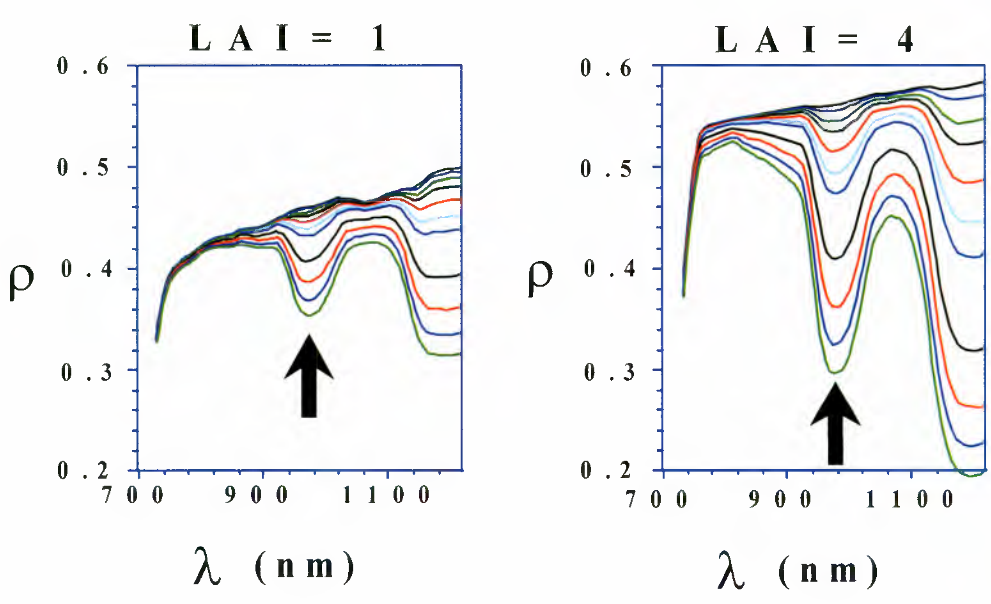

Figure 4.13: *Changes in canopy reflectance as a function of leaf liquid water content, for two different LAI values. Changes are due to multiple scattering effects. These effects must be taken into account in estimating leaf water content from canopy spectra (Courtesy: J. Moreno).*

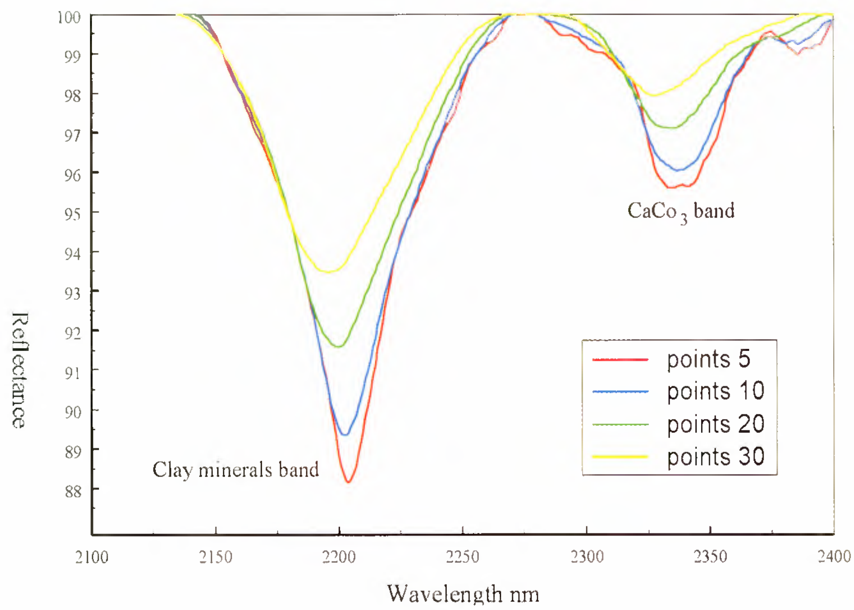

Figure 4.14: *Effect of filtering on depth and position of $CaCO_3$ and clay minerals absorption bands (Leone and Menenti, 2001).*

resolution between the nadir and forward view discussed later, results were quite encouraging. In another study, this method was applied to time series of ATSR-2 observations and the retrieved soil and foliage temperatures were assimilated into an NWP environment (Van den Hurk et al., 2001; see also Chapter 3). Recent work (Sobrino and Cuenca, 1999) provided new insights on the anisotropy of the emissivity of leaves and soils. Measurements showed negligible changes in leaf emissivity with view angle. As regards soils, the experiments provided information on angular changes of emissivity, which can be directly used in the algorithms to separate foliage and soil temperatures.

In 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 parts of the spectrum where specific features can be exploited. Examples include the so-called 'red-edge' exhibited by vegetation canopies around 650-750 nm, or the distinction of liquid water from water vapour absorption bands in the middle infrared. Other examples have been cited or can be found in the literature.

It is also important to keep in mind that land surfaces are always observed through the atmosphere, which can significantly affect the values of the measurements. While the presence of extensive and deep convection clouds is clear enough in remote sensing data, spectrally and spatially, the effects of atmospheric aerosols remain a major source of uncertainty in the interpretation of these data over continents. Here also, a high spectral resolution and data acquisitions at multiple angles of observation have both been shown to improve very significantly the quality and reliability of the retrievals.

New algorithms in this respect have been developed, tested and applied operationally to MODIS and MISR data, and the SPECTRA mission will thus be able to capitalise on these advances, as well as to contribute new approaches.

4.3.3 Spatial and Temporal Sampling

Spatial sampling

Throughout this report we have stressed repeatedly that terrestrial vegetation is heterogeneous at all spatial scales (Figure 4.15). To model landscape processes we need to identify portions that are statistically homogeneous, i.e. mixtures of soil and vegetation in approximately constant fractions and spatial organisations. It is obviously impossible to define a unique spatial resolution to capture and characterise homogeneous elements of all terrestrial biomes in an economical way.

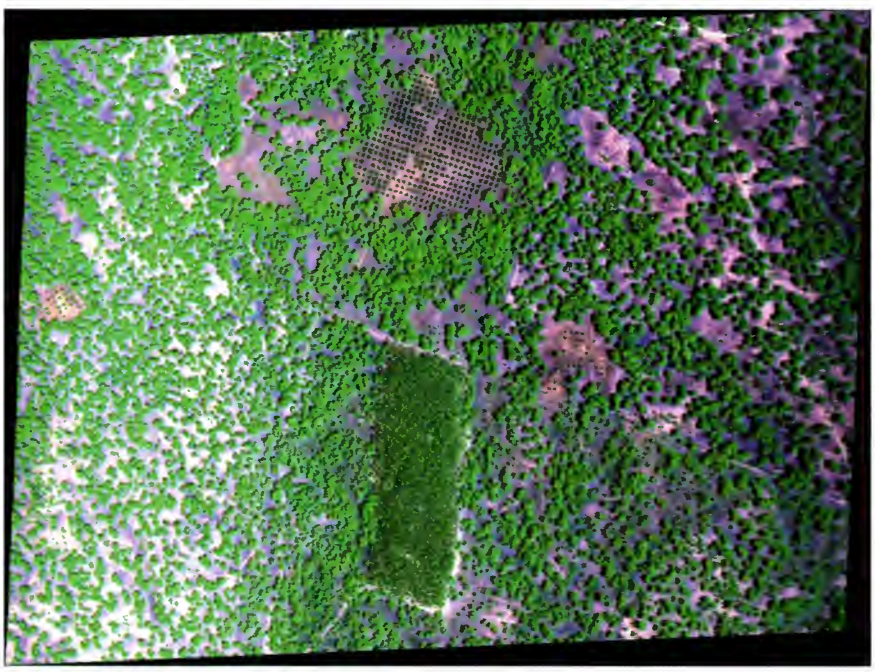

Figure 4.15: *Multispectral airborne image of a managed forest; Daedalus multispectral scanner; Evora, Portugal; 1 m spatial resolution (Courtesy of L. Alonso).*

For the stated purpose of the SPECTRA mission, which is to document the heterogeneity of the landscapes and to permit the scaling up of local observations to regional estimates, it is necessary to acquire observational data at a resolution that is compatible with the scale at which ground measurements may take place, and over regions large enough to be representative of the areas for which parameterisations need to be derived.

Techniques of data interpretation continue to evolve. Mixing analysis, for instance, permits the estimation of the proportions of various constituents within an observed area, with the help of simplifying assumptions. Recently, work by Pinty et al. (2001) showed that the anisotropy of the land surface can be analysed in terms of the heterogeneity of the geophysical media at the sub-pixel resolution.

Specifically, the shape of the BRF field retrieved for a given pixel appears to be related to the structure and organisation of the landscape within that pixel, in the following sense. Homogeneous surfaces, such as bare soils and fully covering canopies exhibit an anisotropy pattern characterised by a 'bowl shape' BRF, where the reflectance is lower when observing the surface from the nadir than from larger zenith angles. However, an environment composed of relatively sparse dark vertical structures over a brighter background (as is often the case for a vegetation canopy over the underlying ground, in the red spectral domain) would appear brighter from the nadir than from oblique observation conditions, because of the predominant effect of the background in that case.

This is shown graphically in Figure 4.16. The red curve represents a typical bowl-shape BRF pattern for homogeneous surfaces (or even linear combinations of homogeneous surfaces), such as the one shown at the top of the figure. This simulated SPECTRA pixel is fully covered by a dense canopy in the left half, and only bare ground in the right half. If all the leaves explicitly represented in this scene are redistributed spatially in clusters as shown in the bottom of the figure, keeping the number of scattering elements and all optical properties identical, a bell shape BRF pattern results. This is the blue curve in the diagram. Hence the spatial organisation of objects within the observed pixel directly affects the anisotropy of the radiation field, and multi-angular measurements such as will be provided by SPECTRA will allow the characterisation of types of heterogeneity at spatial resolutions finer than provided by the elementary observations. These recent developments should lead to new and better descriptions of the terrestrial environments, including more accurate land cover distributions.

As described earlier, the SPECTRA mission is designed to acquire large amounts of detailed data over selected regions where intensive ground investigations are taking place. These field campaigns and other local investigations that will benefit from this mission will cover a wide variety of ecosystems and watersheds of different dimensions. However, past experience shows that even during broad international campaigns, field investigations tend to be concentrated on a restricted number of sites of limited extent. For instance, the HAPEX, FIFE, BOREAS and LBA have all identified dedicated sites for intensive data acquisition and characterisation. The regions covered by the experiments vary in size, but are typically 100 to 2500 km^2.

Such regions exhibit the following characteristics:

- areas of that extent correspond to the typical size of a 'grid square' of atmospheric circulation models (10 to 50 km grid point spacing),

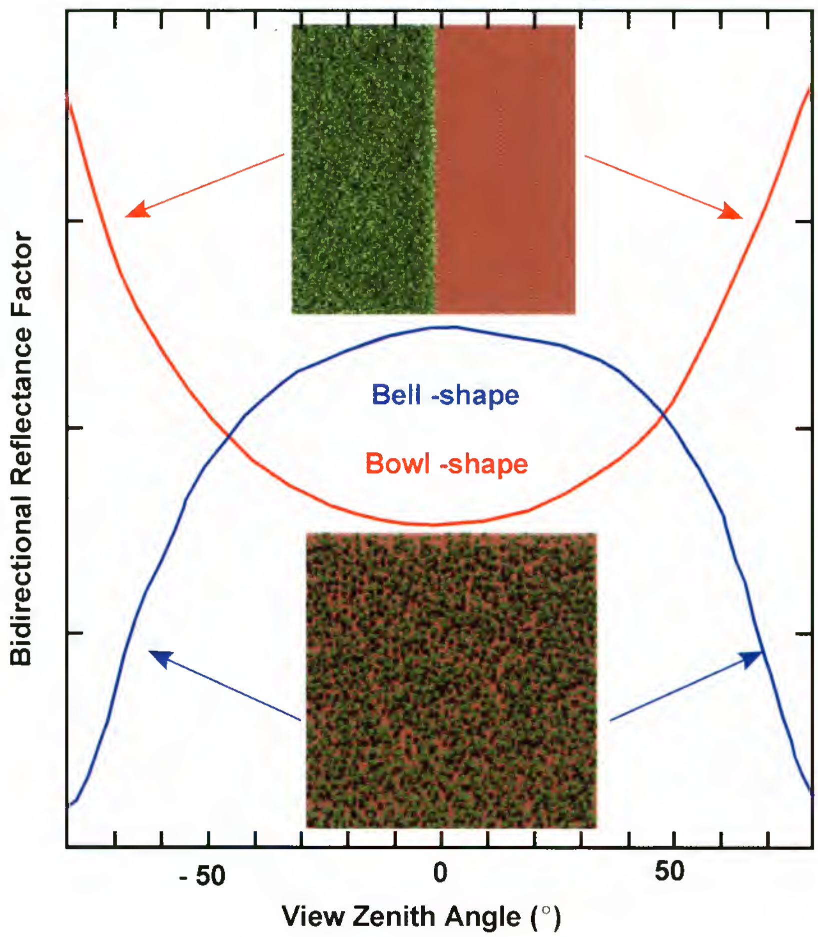

Figure 4.16: *Homogeneous environments (such as that represented in the top panel, with half of the area bare ground and the other half covered by vegetation) exhibit a typical bowl-shape BRF pattern (red curve), with reflectance increasing with observation zenith angle. However, if the leaves from the vegetation canopy are redistributed into individual bushes, as shown in the bottom panel, the reflectance of the environment turns into a bell-shape pattern (blue curve), where the reflectance decreases with observation zenith angle. These BRF patterns may thus reveal structural heterogeneities of the environment at the sub-pixel scale. See the text for additional details (Courtesy: B. Pinty).*

- significant watersheds (larger than individual streams but smaller than entire river basins) include sufficient heterogeneity to enable the simulation of complete landscapes (this size permits the study of critical scaling issues identified earlier),

- local to regional topographic, soil and climatic gradients dominate the landscape and the distribution of ecological variables at that scale,

- meteorological and hydrological field measurement networks are designed to work at that scale, and are usually implemented on watersheds of that size,

- process studies are often conducted at that scale because the collection and processing of data for regions of that size are operationally and logistically feasible.

Given the close relationship between the space and ground segments of this mission, it is essential that the elementary area that can be observed by the SPECTRA instrument (defined by its spatial resolution) be small enough to be fully documented on the ground, so that relations established at the pixel level can be extended to larger areas (i.e. up to the scale of the scene acquired from space). Detailed intensive measurements of Leaf Area Index, leaf chlorophyll or water content, biomass and other variables cannot realistically be carried out over more than one or two hectares, so this places an upper limit on the diameter of the measured area. At the same time, it is desirable to acquire continuous coverage of the area of interest, so the sampling frequency in space must be sufficient for that purpose.

A major attribute of the landscape is its spatial organisation, i.e. the arrangement in space of its different elements. Examples of characterisations of such spatial patterns include the patch size distribution of residual forests, the location of agricultural plots in relation to natural or cultural features, the shapes of fields and the number, type and configuration of landscape elements (their spatial heterogeneity). To detect changes in landscape patterns, the spatial resolution of the sensor must be sufficient to document the average size and properties of the ground elements that need to be resolved. Briggs et al. (1995) showed that there is a monotonic loss of information as the spatial resolution decreases. For complex landscapes, there is no particular spatial resolution threshold at which an abrupt loss of spatial information would occur with increasing resolution. For well-structured landscapes, the existence of a threshold depends on the average parcel size and is therefore different for different landscape types.

Experience with current sensors reveals that with spatial resolutions of 20 to 30 metres, the structure of complex landscapes is resolved in great detail. A slightly coarser spatial resolution would not affect the analysis of surface processes in a major way as most agricultural fields, forest plots or natural landscape units have sizes of several tens of metres. Data layers, which are used in ecological models and which are not derived by remote sensing (e.g. digital elevation models, soil maps, etc.), are generally generated at a coarser spatial resolution. On the other hand, the collection of field observations with ground instruments rarely extends beyond an area of one to a few hectares. An instrument providing a spatial resolution of about 50 metres at nadir would therefore be a good compromise between the needs of various scientific groups. This spatial resolution is expected to be adequate to support all regional studies and field experiments that will take place during the mission.

The proper interpretation of remote sensing data hinges on the assumption that the data from different spectral bands and observation directions actually refer to the same target. The spectral data must therefore be co-registered with the utmost care. It is understood that the area actually observed by the sensor may vary with the angle of observation, especially during BRF acquisitions (depointing along track) or when acquiring data for sites not observable exactly at nadir (depointing across track). The effective interpretation of these data will require that all data sets be re-mapped into a common map projection.

Temporal sampling

The terrestrial processes of interest in the context of this mission exhibit significant daily, seasonal and inter-annual variations, due to such phenomena as El-Niño, major volcanic eruptions and other year-to-year climatic fluctuations. Also, from a programmatic point of view, the detailed investigations typically undertaken in major international field campaigns last at least a few years. The most important environmental changes in the scientific context of the mission are those that vary on a weekly timescale throughout the season. Thus the maximum period between two consecutive useful observations should not be longer than about a week. This will allow efficient assimilation of the data into dynamic models of ecosystems. The presence of clouds that prevent the observation of the Earth's surface is one of the main limitations of optical remote-sensing systems when high-temporal-frequency data acquisition is required. The cloud climatology shows that, on average, about half of the Earth is covered by clouds (Rossow et al., 1988) at any given moment. It is recommended that observations should take place at intervals of about three days.

Data acquisition in the thermal domain has to account for different time scales than those applicable for reflectance in the solar domain. Leaf and soil temperatures may vary significantly more rapidly than the other canopy properties considered so far. Monitoring such changes would require either a geostationary platform (at a severely reduced spatial resolution), or a constellation of platforms. However, the main terms of the energy and water balances could still be estimated correctly by assimilating occasional measurements (at nominal intervals of 3 days to a week) into a dynamic SVAT model.

Field measurements are often undertaken only during limited campaign periods at a given site. The proposed temporal sampling should therefore permit the support of such campaigns with data being provided every few days, assuming that the weather conditions are favourable. This limitation has to be taken into account to plan data acquisition a few days in advance.

4.4 Overview of Requirements

4.4.1 Angular Requirements

As explained earlier, angular observations are required to:

- ***document the anisotropy of the surface*** and account for these effects in the interpretation of the data. This is always necessary, even for near nadir observations, because the position of the Sun varies appreciably during the day and throughout the year, and because land surfaces are anisotropic.

- ***improve significantly the characterisation of the atmosphere,*** building on the work carried out for the POLDER (Leroy et al., 1997) and MISR missions (Martonchik et al., 1998a). This is critical to ensure the quality of the land surface products.

- ***derive additional information on the canopy,*** which cannot be obtained on the basis of spectral data alone; this is obviously the case for albedo estimation, but is also true for the other canopy structural variables, as shown recently by Bicheron and Leroy, 1999; Verhoef and Menenti, 1998; Weiss et al., 2000; Pinty et al., 2001; Menenti et al., 2001).

A minimum of three independent parameters is required to adequately represent the anisotropy pattern of terrestrial surfaces and their overlying atmosphere (e.g. Rahman et al., 1993b): one for the overall level of reflectance, one to describe the bowl- or bell-shape of the anisotropy, and one to characterise the preferential forward or backward regime. A fourth parameter may be needed to adequately represent the hot spot feature, if it is sufficiently sampled.

The characterisation of the anisotropy of the coupled surface atmosphere system is achievable with a minimum of five, and preferably seven, observation angles distributed as follows:

- ***Nadir or near-nadir (in the case of across-track depointing) observations*** are required because they provide the best spatial resolution and the shortest atmospheric path length.

- ***Two observations at large zenith angles*** are necessary to sample the rapid changes in directional reflectance (or emittance), i.e. BRF and BTDF, observed for the largest zenith angles as seen previously. These are required both ***in the forward and in the backward scattering regimes*** in order to document the asymmetry of the BRF and BTDF, a critical factor for differentiating the anisotropy of the atmosphere from that of the underlying surface. In addition, the atmospheric path length is largest at those zenith angles. Observations at zenith angles of exactly 60°

and 70.53° relative to the surface reference ellipsoid would permit measurements through two and three atmospheric (and canopy) path lengths, respectively. Analysis of data gathered with the MISR instrument has demonstrated the usefulness of observations at such large angles for atmosphere characterisation. However, as the observation zenith angle increases, the size of the area observed on the ground also increases, and this complicates the analysis of the data in the ground segment. The mission should thus be conceived in such a way that data may be acquired at angles as large as 70.53°, in particular to help in documenting the state of the atmosphere, and recognising that simpler treatments may be limited to observation angles up to 60° only.

– ***Two other additional observation angles are required to improve the characterisation of the BRF/BTDF, and provide information on the hot spot (backward scattering) or the specular reflectance direction (forward scattering) features of land surfaces whenever these are observable.*** Several theoretical studies have shown the usefulness of observations in the hot spot for better characterising canopy structure in the solar domain (e.g. Verstraete et al., 1990; Pinty et al., 1990; Kuusk, 1991). The angular position of the hot spot is tied to that of the Sun, which is variable in space and in time. These observation angles must therefore be programmable as a function of the site observed and season of the year. The hot spot feature can be sampled only in the principal plane or very close to it. By extension, it is recommended that all angles of observation be selectable so that the optimal angular strategy of observation may be defined in flight, to take full advantage of experience gained during the mission.

Because of the high sensitivity of the BRDF and BTDF 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° of their actual values. This is particularly important at large observation zenith angles, where small errors in angular pointing result in large variations in optical paths and positions on the ground. It is even more critical when sampling the hot spot because of the sharpness of this feature.

As shown earlier, the anisotropy of land surfaces varies with wavelength. It is thus necessary to acquire these directional measurements for at least a representative set of spectral bands. Very limited empirical evidence is currently available in that area, because the directional observations in a large number of spectral bands have never been acquired from space or from airborne sensors before.

A user selectable subset of up to 60 spectral bands in the solar spectral domain of the entire VIS, NIR, SWIR spectrum, plus the two thermal bands, should thus be provided for all the observation directions indicated above. The band selection would necessarily be the same for all angles other than nadir.

4.4.2 Spectral Requirements

The case studies summarised above show that the scientific objectives of the mission (in particular the delivery of reliable, accurate, quantitative estimates of specific biogeophysical variables) will be met by acquiring dense contiguous observations in various spectral intervals within the spectral range between 400 and 2350 nm. These spectral regions include, for instance, the well-known 'red edge' exhibited by vegetation in the region (650–800 nm), and the NIR spectral region (850–1050 nm) where liquid water and water vapour absorption bands are sufficiently separated to be distinguishable. As noted earlier, a minimum of 60 spectral bands in the VIS/NIR/SWIR range, together with the two thermal infrared bands, would satisfy the observational requirements.

Current experience with field and airborne instruments suggests that a spectral resolution, technically defined by the 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 400–2350 nm spectral range. In any case, whenever multiple fine contiguous spectral bands are required, the ***FWHM should not exceed 15 nm.***

The actual spectral position of each and every band must be precisely known and verifiable. The interpretation of the data will rely heavily on the spectral position of neighbouring measurements: even small errors in the spectral position of the channels used in the retrievals can lead to huge deviations in the derived values. Hence, accurate knowledge of the position of the bands is a critical issue for the quantitative retrieval of geophysical variables, 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), each spectral measurement involves two physical variables, namely brightness temperature and emissivity. The interpretation of these measurements is further complicated by the fact that the emissivity of terrestrial materials is quite variable at most wavelengths, although this complication is much less severe in the spectral range 10 to 13 μm than at shorter wavelengths. This is therefore the preferred spectral region for the purpose of 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 skin 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 to 11.5 μm and 11.5 to 12.5 μm, respectively, are considered optimal for the determination of surface temperatures. The FWHM should be close to 0.5 μm. These measurements must be acquired simultaneously for the same geographical locations, and so the thermal spectral measurements must be co-registered, just like the solar spectral measurements. Given the sensitivity of emissivity as a function of wavelength, the actual position of the thermal bands needs to be known to better than 0.1 μm.

One of the most innovative capabilities of this mission will be the acquisition of directional thermal infrared data. This feature is particularly important because it provides a unique opportunity to distinguish between the temperatures of the background soil and of the overlying plant canopy. Both thermal bands are thus required at all acquisition angles.

4.4.3 Radiometric Requirements

Studies conducted for the preparation of this mission show that the radiometric accuracy must be of the order of 2 to 5% (Fourty and Baret, 1997; Verhoef and Menenti, 1998; Weiss et al., 2000). 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 long-wave 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 physical processes that determine the radiation field observable from space platforms affect not only the intensity and angular distribution of the radiation, but also its polarisation. The degree of polarisation may be important under some circumstances, depending on the type and number of atmospheric scatterers, the phase angle, and the wavelength. The possible impact of this polarisation on the measurements acquired by the SPECTRA mission should be minimised to preserve the accuracy of these measurements.

The radiometric requirements can thus be summarised as follows:

- The mission must be able to provide data with a radiometric resolution for the reflective channels (NEdr) in the range of 0.0025, with a radiometric accuracy of 2 to 5%.

- The mission must provide temperatures with a radiometric resolution (NEdT) better than 0.1 K when observing a black body at 300 K. The absolute 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.

4.4.4 Spatial Requirements

The spatial requirements can be summarised as follows:

- The mission must be able to provide data for any site with a latitude of 80° or less, arbitrarily selected anywhere over continental regions.

- 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 size of the individual areas being observed shall not vary by more than 50% as a function of the various zenith angles of observation.

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 such as SPOT HRV and Landsat ETM.

4.4.5 Temporal Requirements

Changes in the condition of terrestrial vegetation are rather rapid during specific growth stages. The rate of change obviously varies significantly, but experience built upon field observations in major biomes leads to the conclusion that one effectively useful 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 (cloud free) conditions. A total duration of 10 minutes for the acquisition of the required five to seven angular samples should not be exceeded.

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 every 2 to 3 days for periods of up to a few months for any given site.

4.5 Summary and Conclusions

The architecture of terrestrial vegetation and the biochemical composition of canopy elements provide an information-rich radiance field in the optical region of the spectrum. Observed spectro-directional radiances are therefore closely related to the required key vegetation properties (Section 3.5). The relation between retrieval accuracy and sampling of the spectro-directional radiance field has been investigated during mission preparation (Verhoef and Menenti, 1998; Menenti, 2001). 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. Spectro-directional radiance was calculated in direct mode with accurate (e.g. ray-tracing) models. The radiance field was then sampled for different combinations of view angles and wavelengths. These simulated observations were finally used to retrieve vegetation properties and estimates compared with the true values (known *a priori*) to determine the error.

The results led to the conclusion that multi-angular observations in 62 spectral bands carefully placed across the VIS/NIR/SWIR/TIR range of the spectrum would provide a sufficient observational base to retrieve the required variables (Table 4.3). Although different RT models and analyses may lead to somewhat different values of the resulting estimated errors, the overall conclusion is that acquiring a comparatively large number of spectral bands from a number of observation angles is a definite advantage over the current situation where a few spectral bands are obtained at a single observation angle. It should be noted that, when using observing systems with limited angular and spectral sampling, accuracy of retrieval may be improved by using e.g. typical BRDFs and *a priori* information on the target observed. It was decided to present two extreme cases (Table 4.3) to provide a measure of the added value of the proposed SPECTRA measurements in comparison with a clearly defined baseline (i.e. the two spectral bands – one view angle case).

The algorithms used to obtain the results in Table 4.3 retrieve different variables from different spectral segments sampled at high spectral resolution (say 10 nm). The scientific objective of determining the soil and foliage temperatures within a mixed target leads to a unique characteristic for SPECTRA: ***the capability to perform nearly simultaneous, multi-angular thermal infrared observations of the same target.***

The arguments developed in this chapter lead to the instrument requirements summarised in Table 4.4.

Variable	Sampling of angular and spectral dimensions	
	1 view angle, 2 bands	*Multiangular, hyperspectral*
Fractional cover	40%	5%
fAPAR	30%	5%
Albedo	30%	2%
LAI	125%	10%
Leaf chlorophyll	85%	10%
Leaf water	Not feasible	20%
Leaf dry matter	Not feasible	20%
Foliage temperature	Not feasible	1 K (mixed target)
Soil temperature	Not feasible	2 K (mixed target)
Fraction living/dead	Not feasible	20%

Table 4.3: *Retrieval error for key properties of terrestrial vegetation; based on results of direct and inverse radiative transfer modelling; 'not feasible' here means 'not feasible with sufficient accuracy to be useful'.*

Mission parameter	Value
Spectral coverage	400 – 2350 nm; 10.5 μm – 12.2 μm
Spectral resolution	10 nm; 0.5 μm
Spectral calibration	1 nm; 0.1 μm
Radiometric accuracy	2%; 1 K
Off-track pointing	± 35°
Along track pointing	Seven angles in the range (0°, ± 70.53°)
Target access frequency	3 days
Swath width	50 km
Spatial sampling	50 m x 50 m at nadir

Table 4.4: *Summary of mission requirements.*

5 Mission Elements

5.1 Introduction

The scientific objectives outlined in Chapter 4 lead to a mission concept in which a spaceborne imaging spectrometer acquires directional measurements over well-characterised sites, with a pre-determined temporal revisit sequence. The mission comprises three key elements (Figure 5.1):

- Field Segment: well-documented and instrumented sites, intensively studied by the teams devoted to the scientific investigation of land-surface processes;
- Space Segment: a single satellite with an imaging spectrometer, providing observations of the selected sites and according to the requirements stated in Chapter 4;
- Ground Segment: satellite operations control and provision of data products.

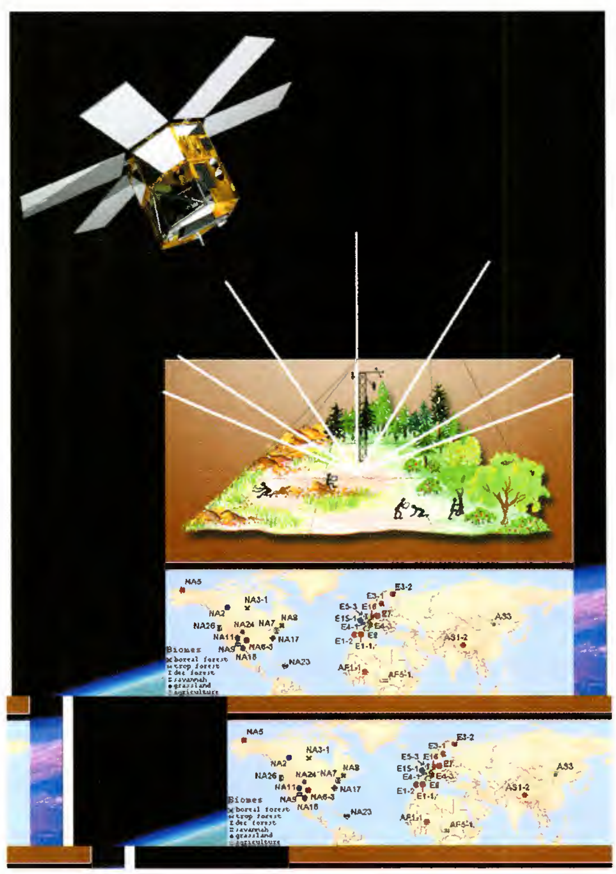

Figure 5.1: The mission concept and its elements.

This chapter shows how the mission science objectives can be met with the proposed space segment, in combination with well-designed field and ground segments.

5.2 The Main Mission Elements

5.2.1 Field Segment

The SPECTRA mission provides global access with high spatial, temporal and spectral angular data. In addition, the scientific objectives of the mission lead to requirements for observations at high spatial resolution and with high temporal frequency (see Chapters 3 and 4). The mission will therefore 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 has been described in Chapters 2 and 3.

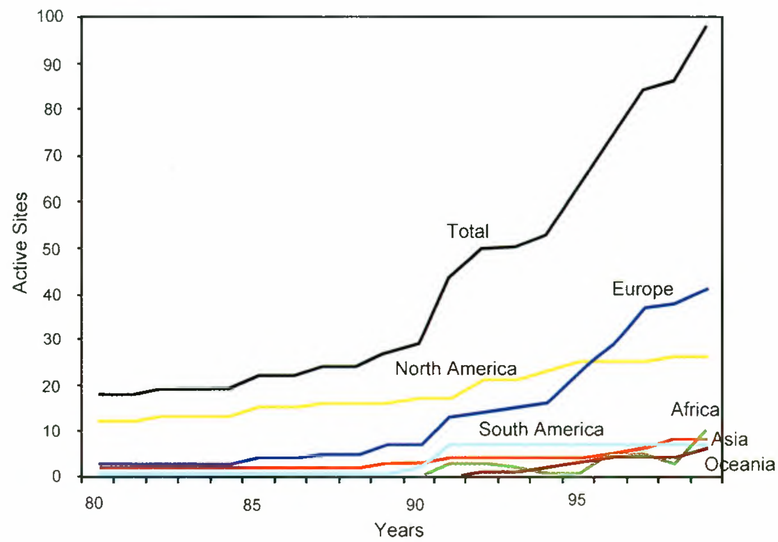

Figure 5.2: *World-wide inventory of Land Surface Experiments: number of sites dedicated to the scientific study of the terrestrial biosphere, by continent and globally (Jacobs and Menenti, 2001).*

It is safe to assume that a sufficient number of representative sites throughout the mission lifetime are available, 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 organised through the IGBP GCTE and BAHC programs and WCRP GEWEX, is developing data standards, lists of key variables and data sharing policies. The site networks are anticipated to be a major feature of the IGBP as it completes its re-organisation. 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 highly resolved time-series of key variables for regions surrounding intensively monitored sites. The spatial resolution of the sensor would allow processes to be resolved to the scale of management units, areas covered homogenously by plant functional types, and soil types, within the footprints of tower and aircraft measurements.

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, useful in testing and developing algorithms for satellite sensor retrievals. In most cases, the sampling design for the above measurements is intended to characterise the local heterogeneity in the ~1 km^2 footprint of the tower, and they may need to be extended to larger scales using a geo-spatial sampling approach to test proposed satellite-based extrapolation techniques. In some cases, as in the US BigFoot project and at a sub-set of Carbo-Euro-Flux sites such a programme has already been implemented.

While we cannot definitively identify the exact sites worldwide that will be funded and operational at launch, 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.

The SPECTRA site network will be have two roles. Firstly, SPECTRA data will allow investigators at a particular site to extend their research, directly, by providing time-series of physical measurements and geophysical data processes for models and for scaling local data to the regional scale. Secondly, the SPECTRA data will allow comparative studies of the responses of ecosystems along major environmental gradients in different disturbance regimes, and in different climate regimes. The availability of uniform data sets and a common strategy for extrapolation and analysis will be a major benefit for the developers of global models, allowing the development of more powerful and general parameterisations.

5.2.2 Space Segment

The mission objectives and the related mission plan place challenging requirements on the space segment. The latter must guarantee coverage of all sites of interest with a revisit period of (at most) 3 days and at a local time over the equator between 10 am and 12 noon, to ensure good illumination conditions.

The science objectives require angular-reflectance measurements to retrieve key variables with sufficient accuracy; therefore the system must also be capable of acquiring directional measurements with an adequate pointing accuracy. The desired angular measurements should cover the following co-elevation angles: ±70°, ±60°, ±45° or ±30°, 0° (or as close as possible to this when the site is not on the satellite ground track).

Spectral measurements in two wavelength regions are required. Region 1 covers the Visible-Near InfraRed (VNIR) and the Short-Wave InfraRed (SWIR) from 0.45 µm to 2.35 µm. Region 2 covers the Thermal Infra-Red (TIR) range from 10.3 to 12.3 µm, and is divided into two spectral bands each with a width of 0.5 µm. Other requirements, e.g. radiometric accuracy, spatial and spectral sampling, are specified in Chapter 4 and will not be repeated here.

The fundamental radiometric magnitudes to be observed are the BRDF and the BTDF (see Chapter 4). An example of sampling the BRDF to obtain Bi-directional Reflectance Factors is shown in Figures 5.3a and b. Likewise sampling of the BTDF is illustrated in Figure 5.3c. This visualises the measurements that will be obtained by SPECTRA for each image pixel. To be precise, SPECTRA will provide a sampling of the BRDF and BTDF, i.e. at the selected seven view angles (e.g. Figure 5.3d).

The spectral-resolution and coverage requirements point to an imaging spectrometer as a feasible technical solution. However, the simultaneous acquisition of all of these spectral bands is not required for the mission's main science objectives. Normally no more than 62 bands (60 in VNIR and SWIR, 2 in TIR), properly selected for each site are sufficient to derive the required variables.

The space segment will provide TOA images of BRDF and BTDF samples, based on accurate radiometric calibration. Each image acquired in a specific direction can be seen as a 3D array of samples, where the first two dimensions cover the spatial extent of the area, and the third dimension covers the spectral domain. To be able to accurately exploit the data, each image needs to be spectrally co-registered (band-to-band), with a goal for the spectral registration accuracy of 15% of the spectral sampling interval and with a goal for the spatial co-registration accuracy of 20% of the spatial sampling interval. In addition, all images observed at the seven view angles will be co-registered.

As will be shown in detail in Chapter 6, a single satellite, carrying an advanced imaging spectrometer, and flying in a Sun-synchronous orbit at an altitude of approx. 670 km, can meet the above requirements. With respect to pointing capabilities, the satellite will be manoeuverable in order to meet the BRDF and BTDF observation requirements and the revisit time objectives. The manoeuverability of the satellite will also reduce its size and complexity.

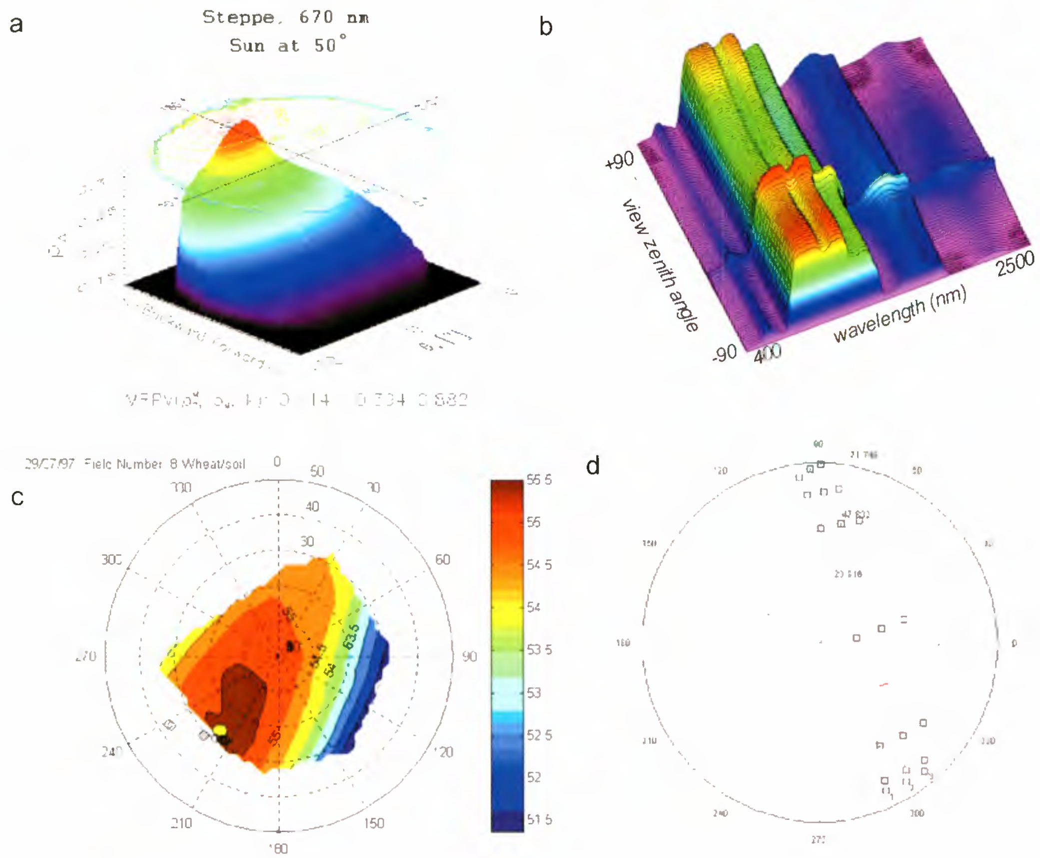

Figure 5.3: *Radiometric magnitudes sampled by SPECTRA: (a) Bi-directional Reflectance Distribution Function at λ = 650 nm; (b) Spectral Bi-directional Reflectance Distribution Factors as a function of wavelength and view zenith angle; (c) Bi-directional Temperature Distribution Function; (d) Along track angular positions of SPECTRA observations during three passes over the same location.*

5.2.3 Ground Segment

The ground segment has to have the following functional elements:

- The *command and data acquisition element*, which is in charge of direct interaction with the satellite for the uplinking of telecommands and the reception of housekeeping telemetry and scientific data. The Kiruna Salmijaervi station is proposed.

- The *mission operations and satellite control element*, which is in charge of implementing the mission plan and controlling the satellite operations.

- The *processing and archiving element*, which is in charge of processing the data to Level-1b, and providing an archiving function and user services.

The processing and archiving element distributes the data to the scientific community. It is expected that the scientific interest will be organised both around intensive site or field campaign studies, and around issues/processes that motivate multi-site or network-wide comparative studies. The ground segment must support users interested in intensive analysis and modelling of one or more scenes, and those interested in comparative or synthetic studies which require data products for all sites.

The concept for the ground-segment facilities is outlined in Chapter 6. Algorithms to derive the geophysical variables required to investigate the land processes have been identified in Chapters 3 and 4. Given the innovative nature of the SPECTRA mission, i.e. the integration of observation and modelling studies of an ensemble of regions worldwide with a space mission, a proper infrastructure will be designed during Phase A (see also Section 6.6) to link the central Processing and Archiving Element effectively with the community of scientific users.

A possible scenario for the SPECTRA Ground Segment could include one or more Scientific Data Centres (SDCs) that, besides providing the TOA calibrated and geo-located radiances (i.e. the so-called Level-1b product) will also provide the geo-biophysical products at Level-2 as identified in Chapter 3.5. Furthermore, these centres would also hold and distribute the associate *in-situ* measured Field Segment data in an agreed format to be distributed together with the SPECTRA Space Segment data. It is envisaged that new data products will also emerge during the course of the mission. Appropriate flexibility should be maintained within the Ground Segment for these.

The complexity of a SPECTRA data set, combined with the geometric corrections necessary to correctly combine the spectral and angular sampling provided for each pixel, will require the development of new procedures. When the regions observed by SPECTRA are characterised by complex topography, two issues have to be addressed:

- Observations of the same target at different view angles have different but unknown image coordinates; an accurate DTM is required to co-register the angular observations, as was demonstrated in the processing of AirMISR observations.

- When the vertical dimension of an object is comparable with the horizontal scale of heterogeneity of the landscape (e.g. tree height comparable with diameter of a clearing), observations at different view angles may relate to completely different objects (e.g. the clearing is not visible at some view angles); in such cases only the observations relating to the same target may be used in algorithms based on angular sampling of BRF.

5.2.4 SPECTRA Mission Operations Plan

Through its across-track pointing capability, SPECTRA has global access capabilities within three days in order to meet the revisit requirement. The mission does not have the task of achieving global coverage in any given time; rather, the emphasis lies on repeated observations of selected regions representative of important biomes, in order to obtain time-series, especially in the case of vegetation during the growing season.

In order to support the analysis of all the major terrestrial biomes, the selected regions will have following characteristics:

- each region should comprise a site contributing to a national or international research programme, such as the IGBP or the WCRP
- each site has to be 'maintained', i.e. *in-situ* surface and atmospheric measurements carried out routinely and collected in time-series databases
- each site has to be represented by one or more principal investigators who commit themselves to providing the *in-situ* data for the scientific analysis of SPECTRA data, if the site is chosen to be a element in the SPECTRA mission and experiment plan
- the ensemble of regions guarantees appropriate sampling of key biomes and farming systems.

A proof-of-concept plan has been developed to use in the testing of targeting and scheduling algorithms. Currently about 50 priority regions (Figure 5.4) have been identified out of 100 candidate sites that, if selected today, would meet the mission's basic science requirements. All of these sites are part of ongoing research activities and/or large international research programmes. In each of the 50 cases, PI's have expressed their interest in cooperation and a desire for satellite data, in the event that their site is eventually selected.

A nominal operational mode has been defined, which is based on a scenario for the 'Mission and Experiment Plan' (MEP). The 50 regions mentioned above have been inserted into a SPECTRA mission simulation (see also Section 6.5), and have been subject to a nominal mission planning, resulting in a representative operational plan. The algorithms developed take account of boundary conditions such as illumination conditions, data recording limits, de-/re-pointing speed of the system, etc. This analysis suggests that a set of sites of the order of 50-100 can be imaged regularly within the principles of the SPECTRA science plan (Figure 5.5).

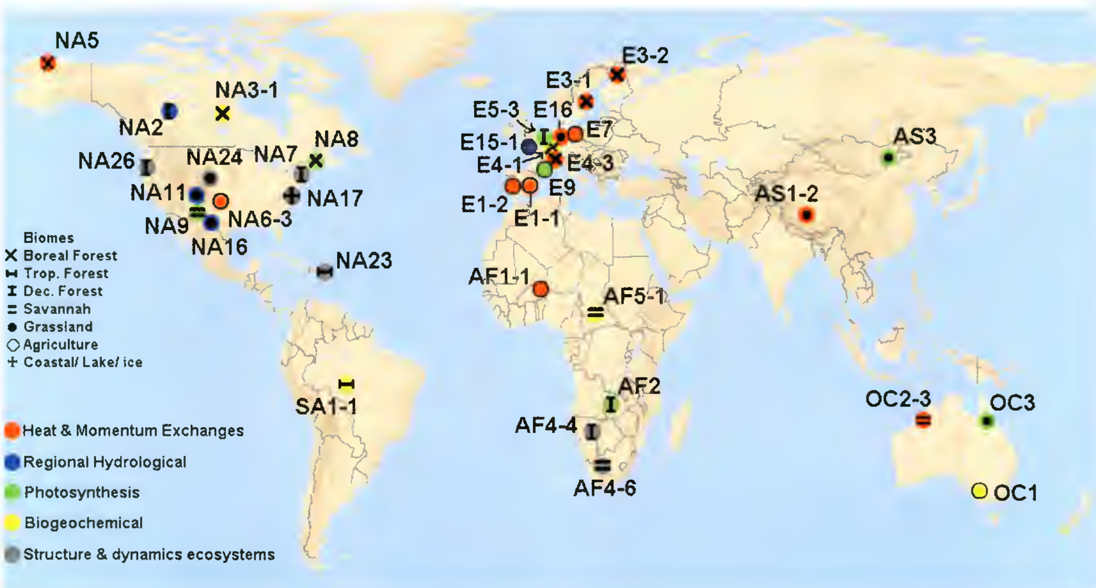

Figure 5.4: *Analysis of a mission scenario based on an arbitrary selection of regions.*

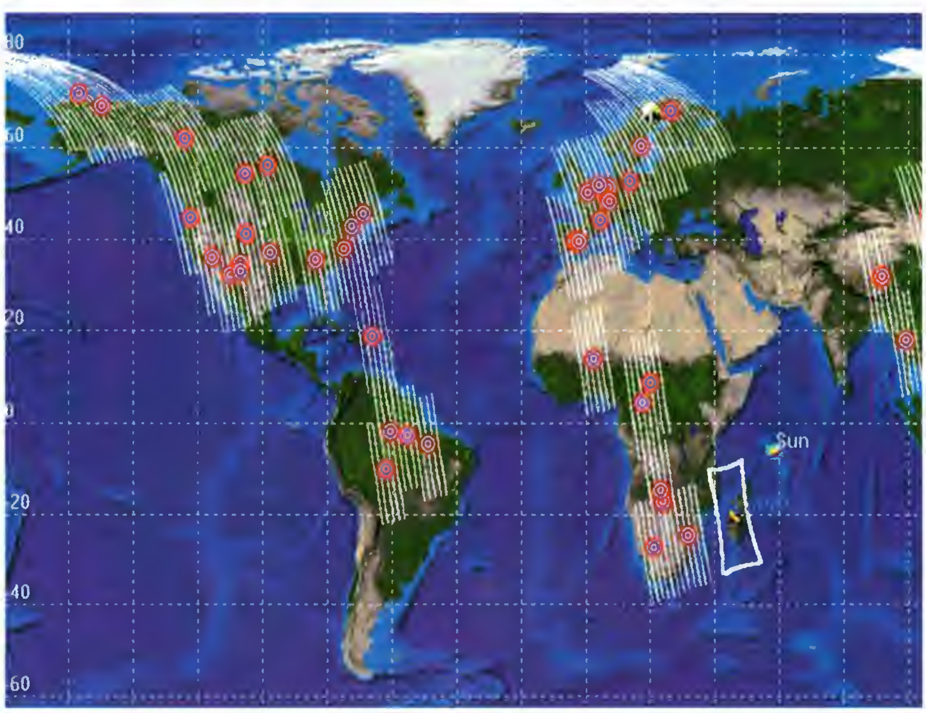

Figure 5.5: *Evaluation of a data acquisition scenario by means of mission simulation and optimisation; white arcs indicate the sub-satellite track during each multi-angular data acquisition; the white rectangle indicates an area where hot-spots can be observed at the indicated Sun position; red circles indicate regions selected for this scenario evaluation.*

The operational concept for the SPECTRA mission foresees the following phases in establishing the mission plan, taking account of potential acquisition conflicts:

- At the time of launch, a tentative set of sites will build the basic SPECTRA mission plan, based on an Announcement of Opportunity (AO) for field-site selection during the preparation of the mission. This set will be selected and implemented by the Agency based on individual site characteristics and overall network strategy and coverage.

- This plan will be flexible to the effect that back-up sites can replace the sites originally selected. This might for instance happen when a site is found to be no longer relevant, or is abandoned or otherwise becomes unsuitable.

- On a shorter time scale, observation conditions such as cloud coverage may be taken into account to prioritise certain sites over others in order to maximise the mission return. In that sense back-up sites or new sites may be selected and implemented in the MEP.

- In case of immediate need, e.g. a suddenly emerging natural hazard, the mission plan can be adjusted by adding the hazard site to the mission planning.

These mission operations and the quoted flexibility will be assured by the SPECTRA Mission Operation Centre (SMOC) which is an element of the SPECTRA Ground Segment. This Centre will be responsible for the satellite's operation and for establishing the data acquisition plan. It will also be responsible for adapting the mission plan when sites are added or removed from the Mission Operation Plan. In addition, the SMOC will handle the prioritisation of site acquisitions, according to predefined and transparent procedures. This is important, for example, if regions included in the current mission plan are under cloud cover for long periods and back-up sites can take their place, or if a site cannot support the mission with the requisite ground observations for an extended period of time.

5.3 Mission Context

5.3.1 Links to the Direct Remote Sensing of Carbon Dioxide

In the past year, researchers have shown that the direct remote sensing of carbon dioxide concentrations in the atmosphere might be feasible, using either passive or active lidar techniques. Several groups are proposing new instruments and one European team is now supported to make preliminary retrievals using a water vapour/temperature instrument (AIRS) to fly in 2001. Use of spaceborne CO_2 data will require the assimilation of satellite measurements using models. A satellite CO_2 mission would be highly complementary to SPECTRA, but not in any way overlapping. SPECTRA will measure vegetation properties that provide understanding of climate sensitivity of terrestrial biomes and the impacts of management and natural disturbance on the carbon balance. A spaceborne CO_2 sensor would provide a constraint on the regional-scale integral of all fluxes, but only indirect information on the biosphere processes determining the observed, mean CO_2 flux over large areas and the sensitivity of the latter to specific changes in land use.

Emerging plans for using satellite CO_2 measurements include a data assimilation system that would combine an atmospheric tracer transport and radiative transport model with terrestrial and oceanic carbon cycle models. The approach proposed for SPECTRA could complement such a global data assimilation system, as illustrated in Chapter 3 (see Figure 3.6). The ensemble of biome-specific models to be delivered by the SPECTRA mission would provide tighter constraints than atmospheric data alone. There would be significant synergy between SPECTRA and a coarser resolution, global coverage, carbon-cycle mission flying at the same time.

5.3.2 Contribution to Other Missions

The SPECTRA mission will very usefully complement global missions by:

validating the biophysical products derived from large swath satellites
The main limitation on the validation of such data lies in the associated coarse spatial resolution. A methodology has been developed to scale up local field biophysical measurements to large swath satellites. The SPECTRA network of regions will provide a very suitable basis for such validation activity;

improving the surface parameterisation
For carbon and water cycle studies at the regional to global scale, the SPECTRA mission will allow more efficient use of large swath sensor data by developing up-scaling methods and more accurate models for interpretation.

For meteorological applications, observations acquired by meteorological satellites are assimilated into GCM's. The GCM's are based on a description of the surface schemes that simulate the exchange of water and energy between the surface and the atmosphere. SPECTRA will provide a very pertinent way to evaluate and improve surface scheme modules over the network of sites.

For food and fibre production investigation. The estimation of food and fibre production at regional to larger scales is critical for food security and related policy making. Currently, large swath satellites are used in a very empirical way. Moreover, the associated spatial resolution represents a strong limitation on the use of their data for accurate production estimation. Because the processes involved in the bottom-up approach for carbon investigation constitute the core of production models, SPECTRA will provide a unique way to develop and validate such models, at the regional scale, and enable scaling-up of the results, based on large swath data and land use maps.

improving algorithms
The SPECTRA mission will support the building of a library of reference spectra and BRDF's for all biomes. This information can be used to develop accurate algorithms to analyse radiometric data limited to few spectral channels and a single view angle. The algorithms (Knyazikhin et al., 1999) currently used to process MODIS data, for example, make use of a BRDF library derived from the literature. A similar approach could be applied to the multispectral images on-board meteorological satellites.

5.3.3 Contribution from Other Missions

Several novel measurement concepts could be explored by combining the SPECTRA observations with observations that might be provided by advanced missions now in different stages of development:

Vegetation Canopy Lidar (VCL)
This mission aims at deriving interception profiles within the vegetation (Dubayah et al., 2000). It will help in refining the canopy structure description. The corresponding spatial resolution would be consistent with the performance of SPECTRA, although the particular sampling (transects) may not always overlap all of the SPECTRA sites.

Hyperspectral missions
Hyperspectral instruments have already been or are about to be launched; Hyperion (Pearlman et al., 2000) on EO1 by NASA and CHRIS (Cutter et al., 2000) on the PROBA platform by ESA. In the next few years, ASI plans to launch HyPSEO, a technological demonstrator of hyperspectral observations in the VIS through SWIR region. These instruments are prototypes that are designed to validate new technological solutions and concepts. They are associated with low and uncertain revisit capacity, limited swath, and limited radiometric performances. Furthermore, they will also have a relatively short lifetime and give limited access to the data. Nevertheless, they offer a very interesting opportunity to evaluate and develop retrieval algorithms based on their improved spectral sampling capacity.

Earth-observation missions
These are evolving increasingly towards high spatial resolution, already in the order of 1 m. Although such coverage is not frequent, it may provide precise and useful information on the spatial organisation of vegetation canopies. The latter may include the species composition and the size of the tree crowns. For sparse canopies, it could be also very helpful to characterise the cover fraction.

5.4 Conclusion

The nature of land-surface process studies calls for a significant effort on the part of scientists, comparing their model predictions against observations in large-scale field campaigns. This community of modellers and experimenters, together with the networks of test sites and transect studies, constitutes an important third element of the mission, beyond the usual space and ground segments. The ground segment itself will do more than basic processing, and should comprise a dedicated set of processing centres, exploiting well-tested, sophisticated retrieval algorithms. A novel space element will therefore deliver a large number of geophysical data products at the scale needed by the highly diverse scientific community. This balanced combination constitutes a unique opportunity to make significant advances in surface process research, as well as enhancing the value of other missions.

6 System Concept

6.1 Introduction

This chapter describes the SPECTRA system technical concept, which consists of a highly manoeuvrable satellite carrying a hyperspectral imager, the ground segment and the field segment.

6.2 System Requirements

The SPECTRA mission requires that a number of selected sites be observed within three days. Moreover, in a given pass, selected sites (up to three per orbit) have to be observed from at least seven different along-track angles. This allows sampling of the Bi-directional Reflectance Distribution Function (BRDF) of the concerned site and its overlying atmosphere. For each acquisition, the instrument produces a set of spectral images, measured simultaneously in different wavelength regions. When looking at nadir, the image is 50 km x 50 km, the spatial sampling interval and the spatial width (spatial resolution) are 50 m at nadir. The spatial width is required to remain as constant as possible when varying the viewing angle (BRDF angle) and, in any case, is not to exceed 150 m for extreme BRDF angles. This is a major driver for the proposed observation system.

The images in all bands and for all pointing directions are spatially and spectrally co-registered for accurate exploitation of the data. The proposed instrument concept covers two main spectral regions: Region 1, from 0.45 to 2.35 μm (with a goal from 0.4 to 2.4 μm) covers the Visible-Near InfraRed (VNIR) and the Short Wave InfraRed (SWIR). In this region, the instrument operates as an imaging spectrometer with a maximum spectral sampling of 10 nm. Region 2 covers the Thermal InfraRed (TIR), with two bands (10.3-11.3 μm and 11.3-12.3 μm). Up to 60 selectable bands in VNIR/SWIR and the two TIR bands, will nominally be downloaded when observing sites at along-track angles other than nadir. However, the system is capable of acquiring all bands for each directional observation. The physical parameter directly measured by the instrument is the TOA radiance of the selected ground sites. The images are calibrated so as to assign an absolute radiometric value to each of their picture elements. In order to cope with the BRDF angular acquisitions, agile satellite concepts have been baselined to perform the required manoeuvres. Table 6.1 gives an overview of the main SPECTRA system requirements.

The proposed solution for the ground segment envisages the reuse, as far as possible, of ESA ground segment infrastructure, in particular for the Command and Data Acquisition Element (CDAE) and the Mission Operations and Control Element (MSCE). It is intended to develop a specific Processing and Archiving Element (PAE), given the very specific nature of SPECTRA's needs.

Directional requirements	
Across-track depointing capability for 3 days access	± 35°
Directional sequence in BRDF acquisition mode	Observations at 7 zenith angles (programmable, typically ± 70.53°, ± 60°, ± 45° and 0° or ± 60°, ± 54°, ± 30° and 0°) relative to the surface reference ellipsoid.
Pointing requirements	
Pointing error & geolocation without ground control points	< 2.5 km
Spatial requirements	
Image swath and length	50 km
Spatial Sampling Interval (SSI)	< 50 m for any along track angle
Spatial width	< 50 m nadir < 150 m for 70° BRDF angle in Region 1 < 150 m for 55° BRDF angle in Region 2
Spatial misregistration within Regions1 and 2	< 0.2 SSI
Spatial misregistration between Regions 1 and 2	< 4 SSI centre of images
Spectral requirements in Region 1	
Spectral coverage	0.45 to 2.35 μm required 0.4 to 2.4 μm goal
Spectral Sampling Interval (SpeSI)	< 10 nm
Spectral width	< 1.2 SpeSI
Spectral misregistration	< 0.15 SpeSI
Knowledge of centre wavelength/spectral width	< 0.5 nm (TBC) / 0.5 nm (TBC)
Spectral requirements in Region 2	
Spectral coverage	TIR1: 10.3 to 11.3 μm TIR2: 11.3 to 12.3 μm
Knowledge of the wavelength/spectral width	< 0.1 μm / < 0.1 μm
Radiometric requirements in Region 1	
Radiometric resolution	NEdL envelope specified
Absolute radiometric accuracy	2 to 5 %
Radiometric requirements in Region 2	
Temperature range	Between 212 K and 345 K
Radiometric resolution	NEDT < 0.1 K at 300 K
Absolute radiometric accuracy	Tmin- 240K : 5 K / 270 K : 2 K / 345 K : 1 K

Table 6.1: *SPECTRA main observation requirements.*

6.3 Payload

6.3.1 Introduction

The SPECTRA instrument combines the main features of a Visible, Near- and Short-wave-InfraRed (VNIR/SWIR) imaging spectrometer and a Thermal InfraRed (TIR) imaging radiometer. Two parallel industrial studies have produced concepts fulfilling the requirements within the given system constraints. Both concepts are based on a pushbroom type of imaging spectrometer in which the entire field of view is imaged on to a detector array, and benefit from a spacecraft slow-down pitch manoeuvre to achieve the necessary radiometric performance. The main difference between the two concepts is the functionality assigned to the front-end optics (entrance telescope). In Concept A a single common telescope is used to collect light and direct it to the VNIR/SWIR spectrometer and TIR relay optics, while in Concept B two separate entrance telescopes are used to serve the VNIR/SWIR and the TIR channels. Both concepts are described below.

6.3.2 Payload Design

Concept A

In this concept the optical layout includes a pointing mirror, a common telescope, Region 1/Region 2 spectral separation optics, TIR relay optics and the VNIR/SWIR spectrometer.

The pointing mirror has the dual function of pointing the instrument field of view over the required range of ±35° in the across-track direction and of addressing the sources used for instrument calibration, such as the Sun diffusers for VNIR/SWIR and the calibration blackbody for TIR. This pointing mirror has quite large dimensions (600 mm x 250 mm), due to the 250 mm pupil diameter needed in the TIR to compensate for the diffraction effect and to reach the desired spatial width performance.

The front common telescope is a three-mirror anastigmat, with a pupil diameter of 250 mm, of which only 150 mm is needed for VNIR/SWIR. The focal length is 500 mm, leading to an f-number of 2 in TIR and larger than 3 in VNIR/SWIR. The spectral separation between Region 1 and 2 is performed in-field, at the telescope focal plane, which coincides with the spectrometer entrance slit. Reflective areas on each side of the slit reflect the TIR beam towards the TIR relay optics. The latter performs the coupling between the telescope and the TIR focal plane. It is a fully refractive, compact design providing a real pupil in front of the detector, which operates as a cold stop.

The VNIR/SWIR spectrometer is an Offner relay with curved prisms. Its entrance slit is used as an along-track field stop, allowing optimisation of the off-nadir spatial width. It has been optimised to meet the requirement of a maximum spectral sampling interval of 10 nm, for a detector pitch of 30 μm in the spectral direction. Since the required pupil is smaller in VNIR/SWIR than in TIR, a pupil reduction is performed within the spectrometer. The final separation between VNIR and SWIR is performed by a dichroic beamsplitter. Concept A is shown in Figure 6.1.

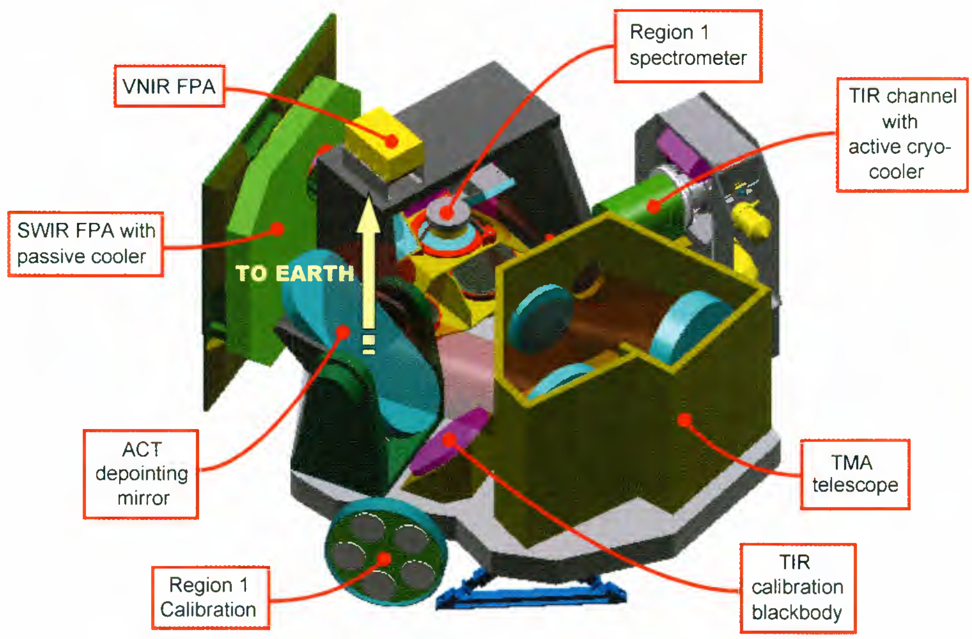

Figure 6.1: *Overview of SPECTRA instrument architecture (Concept A).*

For VNIR/SWIR channels, the radiometric calibration uses two Sun diffusers associated with a multi-function filter wheel. The first diffuser is used, nominally each week, to provide a reference input radiance for absolute and relative spatial radiometric calibration. The filter wheel is placed on the Sun incoming path, and provides shuttering, transmission filtering, and spectral filtering. The second diffuser is normally protected and allows occasional monitoring of the possible ageing of the nominal diffuser. The spectral calibration in VNIR/SWIR involves a rare earth spectral filter located on the Sun incoming path. The wavelength knowledge is obtained by the localisation on-board of a reference wavelength peak position. For the TIR channels, the radiometric calibration is performed before each image sequence using two internal blackbodies; one is cooled to about 200 K, the other about 300 K. These blackbodies are addressed using a special mechanism and mirror, located before the TIR focal plane. The absolute calibration uses a front blackbody addressed by the front end pointing mirror, and possibly cold space viewing during eclipse. The temperature of the absolute calibration blackbody can be changed, to provide a multiple-point calibration.

The VNIR detector baseline is a back-thinned silicon CCD with four output ports. The number of elements is 1250 x 132 effective pixels. The output rate is about 1.5 MHz. Its design benefits greatly from the MERIS CCD development heritage. The SWIR focal plane is directly derived from the SWIR FPA (HgCdTe) being developed by ESA for hyperspectral applications. The number of spectral pixels required is 177, which is fully compatible with the 256 spectral pixels provided by the detector. To reach the 50 km swath, 1250 elements are needed in the across-track dimension. The array is cooled to the operating temperature of about 170 K by means of a Peltier cooler, connected to a passive radiator for thermal dissipation. The TIR focal plane is based on HgCdTe detectors in this spectral range. The baseline uses the hybridisation of both detecting devices and readout circuits on a common interconnect circuit (non-direct hybridisation). The readout circuits are silicon CMOS multiplexers. The HgCdTe modules will have dedicated cut-off wavelengths: about 11.7 for TIR1 and 12.8 μm for TIR2. The required operating temperature, of the order of 60 K to 70 K, is achieved by using two active cryocoolers, in a back-to-back configuration to minimise vibrations.

The instrument electrical architecture is based on four electronic units: the analogue processing unit, for the focal plane management and the signal conditioning up to the ADC, the mass memory unit, which also provides lossless compression and formatting of the data, the instrument control unit for power distribution, control/command of the instrument units and TM/TC interfaces with the platform and the cryo-cooler control unit, specifically in charge of control and regulation of the TIR active cooler.

The mechanical architecture of the instrument is based on a modular approach, as shown in Figure 6.1. Each unit is assembled and tested individually then assembled on a common main bench. A challenge is to guarantee excellent mechanical stability of the spectrometer, to achieve the required registration performance. The accommodation is strongly driven by thermal constraints: the radiator of the SWIR cooler is located on the coldest face, and that of the active cooler on a radiative face. The Sun diffuser entrance is located so as to allow a view of the Sun close to the south orbital pole.

Concept B

In this concept, the approach of using two separate cameras for the VNIR/SWIR and TIR wavelength range, each with its own optimised telescope, has been retained (Figure 6.2).

The VNIR/SWIR camera comprises a pointing mirror, a telescope, which images a ground line on the slit, and a spectrometer. The function of the pointing mirror in this concept is to address the source used for instrument calibration, in this case a Sun diffuser. The telescope is a classical three-mirror anastigmat. It has an entrance pupil diameter of 150 mm and a focal length of 440 mm. The spectrometer is based on an Offner-type relay. The slit has a dimension of 14 μm, giving spectral sampling of 10 nm over the whole spectral range, for a pixel pitch of 30 μm. The spectral domain is split into two sub-domains, each using a dedicated detector, by means of a dichroic plate.

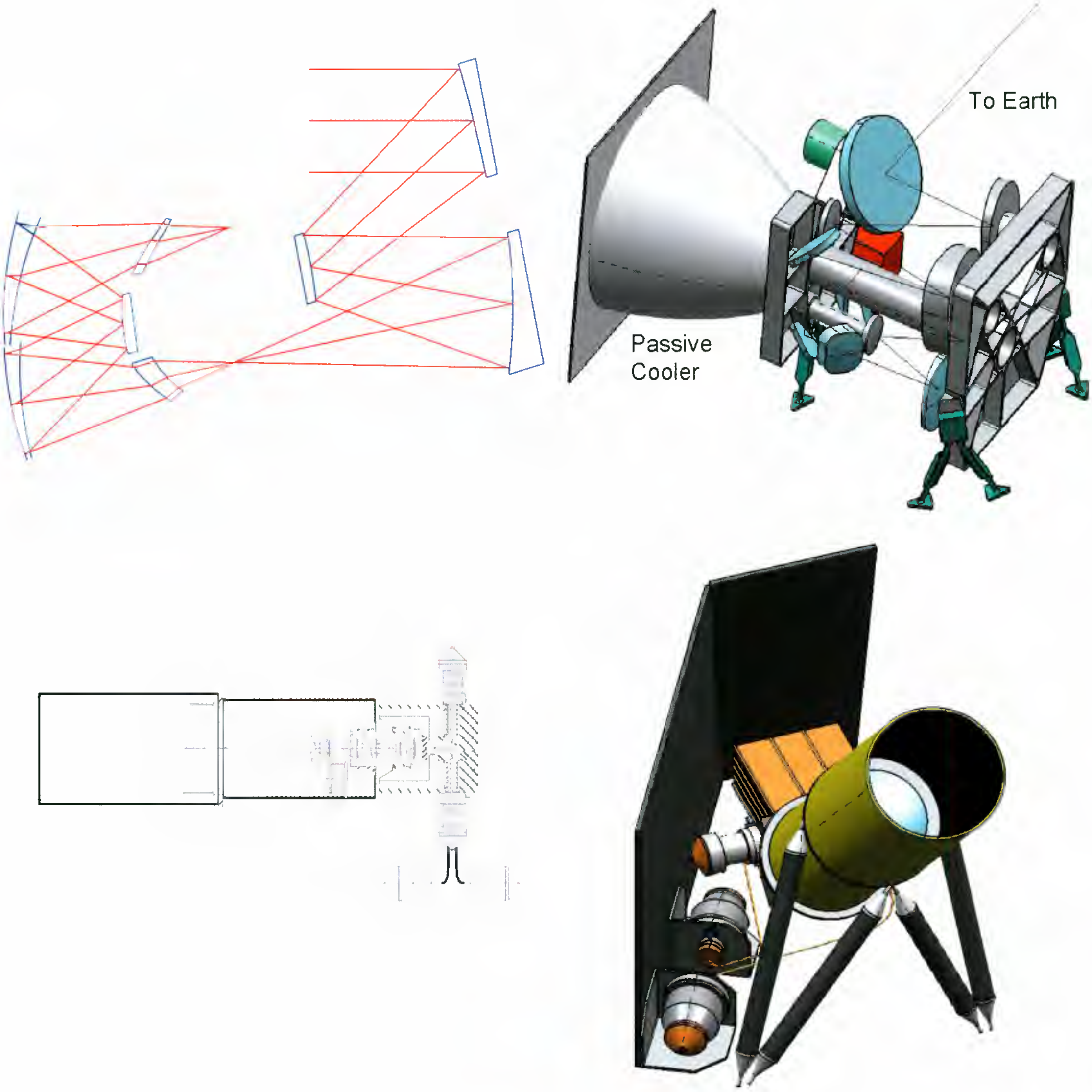

Figure 6.2: *The two separate cameras of Concept B. Above the VNIR/SWUR camera, below the TIR camera.*

An on-axis refractive design is selected for the TIR channel. It includes a front lens in germanium (Ge), a relay optics made of two Ge lenses, combined with a zinc selenide (ZnSe) lens for chromatism correction, and a Ge reverse eye piece, housed in the cryostat for the final imaging onto the detector array. The Ge has the advantage of having a high refractive index, allowing high aperture correction with a minimum number of elements and a low dispersion such that the chromatic abberation between the two TIR bands can be easily corrected. The main drawback is its extremely variable refractive index with temperature. The design shown remains compatible with the spatial width requirements only within a temperature range of ±1 K around the best focus position. This constraint calls for accurate thermal control of the telescope cavity. For that purpose, a long entrance baffle is implemented, and the complete instrument is thermally insulated from the spacecraft environment by MLI. The telescope cavity will be controlled to within ±0.5 K of the nominal operating point.

Calibration of the VNIR and SWIR channel is performed by viewing a diffuser, illuminated by the Sun during a specific spacecraft calibration sequence, via the pointing mirror which is rotated by about 45° to direct the optical beam to the calibration assembly. Other calibration sources to be used for spectral calibration can be inserted into the field of view. The calibration principle for the TIR channel is only based on the use of internal calibration sources, combined with periodic deep-space offset corrections. In addition to the above calibration process, the temperature of the front lens is continuously monitored in temperature to check background signal stability and enable correction if necessary.

In concept B the baseline detector for the VNIR range is based on CMOS technology, and consists of a detection area hybridised on a multiplexer. This technology offers flexibility to compensate for non-linear dispersion of the spectrometer and can potentially simplify the detection chain. Such technology is still under development in Europe. The SWIR focal plane is directly derived from the SWIR FPA (HgCdTe) being developed by ESA for hyperspectral applications. Concept B makes use of a passive cooler to achieve the SWIR detector operating temperature. The design is based on a double stage concept using concave reflector geometry. The first stage of the cooler provides a medium temperature environment to the cold stage and an intermediate cold stop in front of the detector array. The detector array is mounted on the cold second stage. The baseline for the TIR detectors is the same as for Concept A.

The payload electrical architecture is based on the same elements as those present in Concept A. The mechanical architecture of Concept B is shown in Figure 6.2. The VNIR/SWIR module is mounted on the spacecraft platform with the passive cooler on the anti-Sun side inclined by 10° with respect to the spacecraft wall. The TIR camera includes: an entrance baffle; the camera main structure supporting the front lens and the collimating optics; the calibration unit, including the mechanism and two IR calibration sources; the cryostat, including the focussing optics; the detector array, and the cryocooler displacers.

6.3.3 Performance

The proposed instrument concepts achieve very similar spectral, spatial and radiometric performances. For this reason only one set of performances will be reviewed in the following.

Spectral

The spectral sampling performance is shown in Figure 6.3. The maximum spectral sampling interval is 10 nm as required. All other spectral requirements are also met.

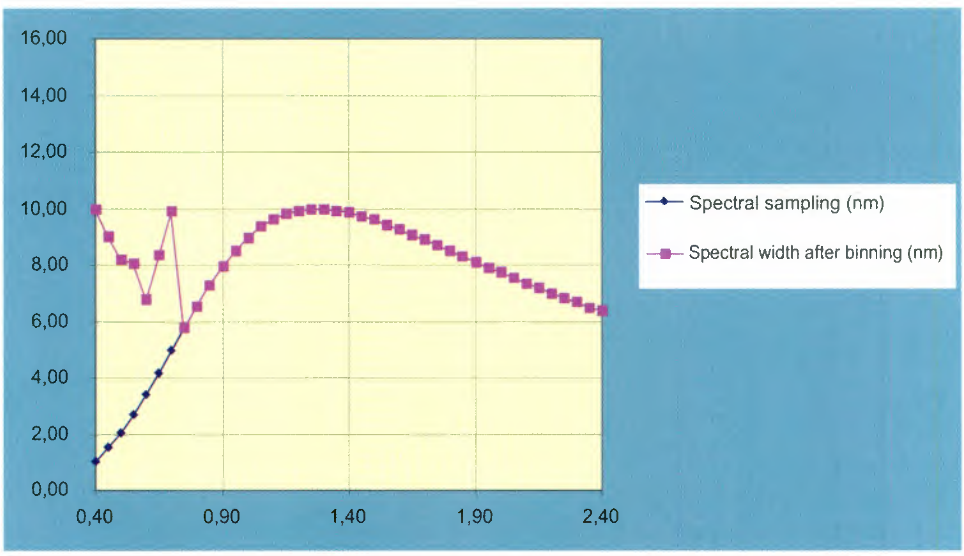

Figure 6.3: *Spectral sampling interval in Region 1.*

Spatial

A main performance driver of the instrument is the spatial width requirement, and in particular at extreme BRDF angles (70° co-elevation from ground, 0° roll). The instrument has been optimised to limit the degradation of the spatial width when the instrument departs from nadir view, in BRDF acquisition mode. This has been achieved by optimising the different factors contributing to the convolution of the spatial width; namely the optics, the geometrical instantaneous field of view and the integration time (gate function). As shown in Figure 6.4, the spatial width is 50 m at nadir in all bands, and remains lower than 150 m at extreme BRDF angles in VNIR/SWIR. The same performance is achieved in TIR for a maximum BRDF angle of 58°. All other spatial requirements (swath, co-registration of channels, spatial sampling interval) are met.

Radiometric

The radiometric resolution performance is shown in Figure 6.5. The performance is better than the requirement over most of the spectrum, except in the lower part of the VNIR, though this is acceptable for the mission. The spatial radiometric accuracy is also estimated to be largely within the requirements. All other radiometric performances are met.

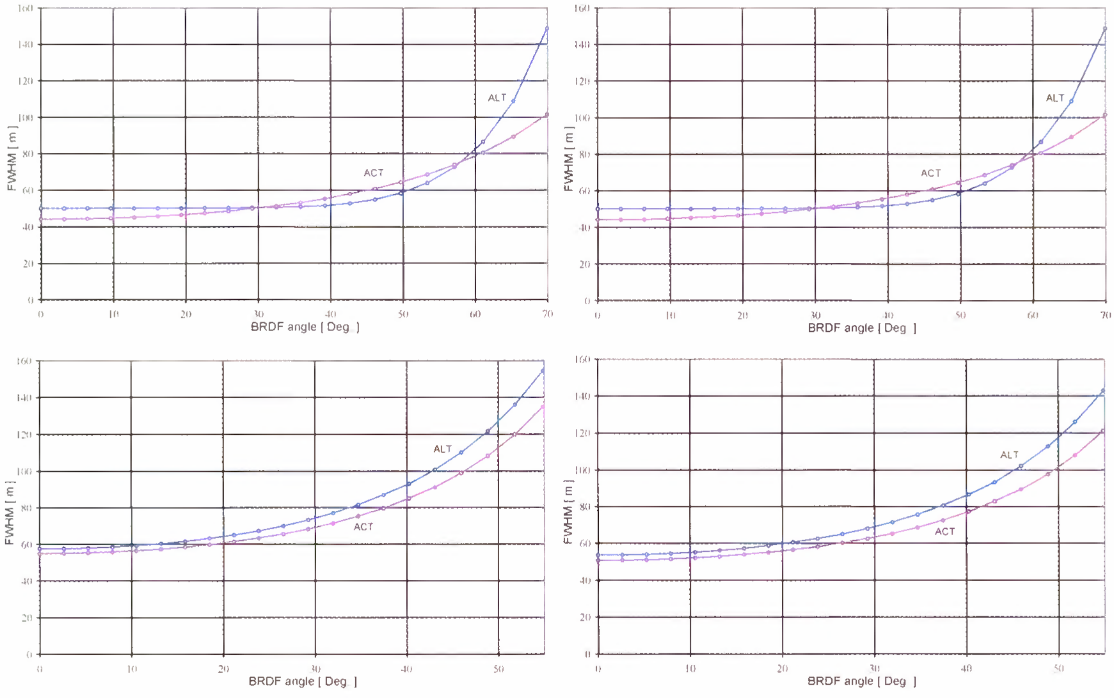

Figure 6.4: *Along-track (ALT) and across-track (ACT) spatial width vs. BRDF angle, for the along-track pointing direction. VNIR (upper left), SWIR (upper right), TIR band A (lower left) and band B (lower right).*

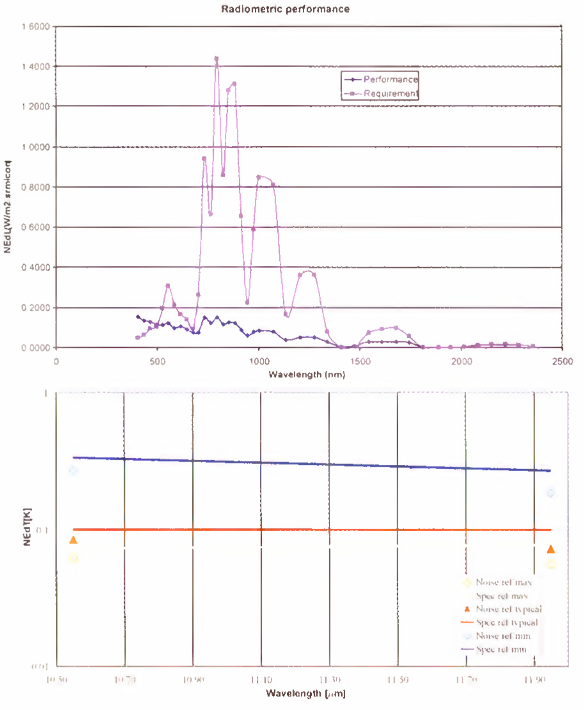

Figure 6.5: *Radiometric performance in VNIR/SWIR (top) and TIR (bottom).*

6.4 Spacecraft

The proposed SPECTRA satellite is based on a modular approach. It consists of the instrument, the payload service module (PLM), including all functions supporting the instrument operations, and the bus service module (BSM) including all satellite functions. The service module is implemented in the form of a hexagonal structure, connected to a central tube by means of shear walls, and offers fixation points to the six deployable solar arrays, which are hinged at the base. The structure is compatible with several launcher adapters since the interface ring may be varied in diameter from 880 mm to 1165.5 mm. The configuration is shown in Figure 6.6.

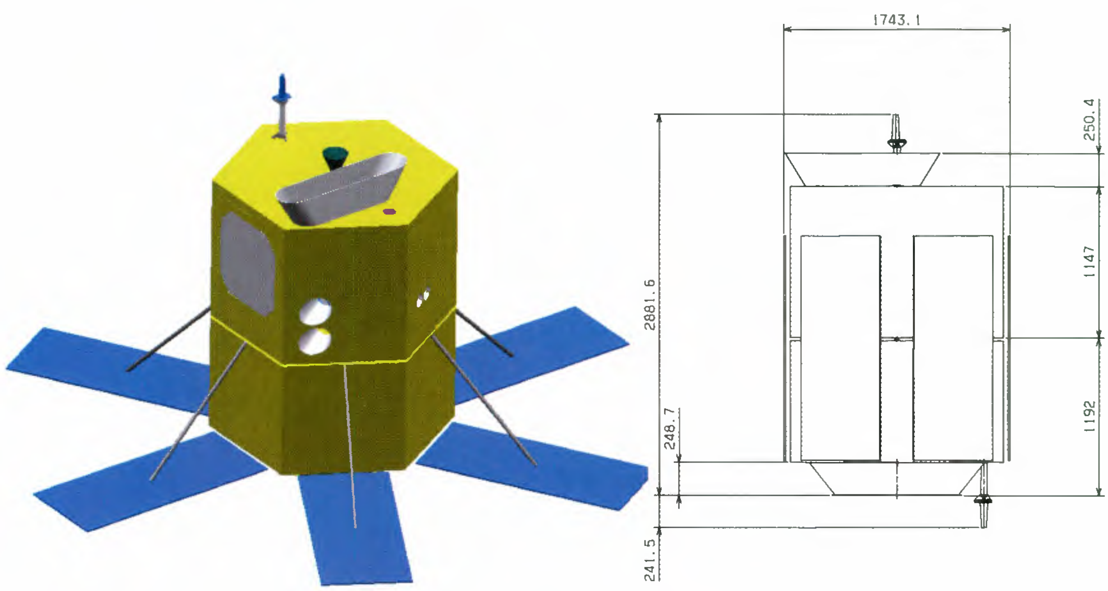

Figure 6.6: *Satellite architecture.*

The thermal control architecture closely follows the modular design described above. The Payload Module is thermally decoupled from the BSM. In particular, cooling of the SWIR focal plane down to 180 K is ensured either by a dedicated passive cooler or by a Peltier element connected to a dedicated radiator, depending on the specific instrument concept. The TIR focal plane is cooled to 70 K by means of cryocoolers. The coolers are mounted on a special radiator, viewing the average anti-Sun direction. The BSM uses passive means to assure an internal temperature within a -20/+45°C temperature range. These temperatures are obtained by using Second Surface Mirrors on the external faces of the lateral panel. The inside of the BSM will be painted black in order to couple all surfaces and achieve a homogeneous thermal environment. Heaters will be placed together with thermistors and thermostats depending on specific unit requirements.

For power generation, six deployable GaAs solar array wings, of one panel each, are fixed to the spacecraft structure. Energy storage will be based on a 78 Ah Li-ion battery linked to an unregulated bus.

RF communications are performed in S-band for ground telecommand and housekeeping telemetry, in accordance with ESA standards. A set of two semi-omnidirectional antennas allows signal reception and emission with full space coverage. The TT&C assembly provides a telecommand uplink bit rate of 4 kbit/s. The payload data will be downlinked in X-band at more than 100 Mbit/s. Antenna pointing towards the ground station is performed by spacecraft orientation.

The Data Handling & Control electrical architecture involves: the Spacecraft Management Unit (SMU), as the platform controller integrating AOCS and DH&C functions and the Instrument Control Unit (ICU) as the instrument controller, where the SMU communicates with the ICU through a 1553B bus. The ICU acts as front-end for the SPECTRA instrument and related equipment (Analogue Processing Unit (APU) and Cryogenic Cooler Unit (CCU)). It is an intelligent unit monitored and controlled by the SMU which is responsible for the overall co-ordination and control of the instrument in the various operating modes. The SMU, as the core of the data system, controls SPECTRA operations, checks attitude control, collects and stores telemetry, maintains time, interfaces the instrument through the ICU and supervises the Mass Memory Unit (MMU). It provides the main synchronisation events of the payload timeline. It also provides all platform control and monitoring interfaces to subsystem/units not directly interfacing to the 1553 bus. The interfaces are to the AOCS sensors and actuators, power and thermal subsystems. The storage capacity will be higher than 100 Gbit. Existing hardware with 200 Gbit storage capacity will lead to sufficient margin.

The two proposed spacecraft concepts present slightly different implementations concerning the agility concept.

Concept A is a partially agile configuration, for which pitch and yaw pointing is performed by satellite manoeuvres and the across-track pointing is performed by the use of a roll pointing mirror. The reference core of the attitude estimation is a large field of view star tracker mounted close to the satellite Y-axis. The actuation capability is provided by 0.4 Nm/8 Nm reaction wheels in an optimised skewed configuration providing a maximal torque capability on the pitch axis. The momentum off-loading is performed by magnetotorquers.

Concept B uses a set of four 15 Nm control momentum gyros mounted in a tetrahedral configuration to achieve a fully agile satellite, enabling control of all axes to achieve the pointing requirements. The satellite is three-axis controlled according to a classic gyro-stellar architecture. Three redundant magnetic torquer bars are used for wheel off-loading.

The Sun acquisition mode orients the fixed solar arrays towards the Sun to set the satellite into a safe attitude whatever the initial attitude. This mode is based on a very robust attitude estimation based on coarse Sun sensors, magnetometers and actuated by the magnetotorquers. Four double-seat 1 N hydrazine thrusters located below the satellite are used for orbit correction and maintenance manoeuvres.

Satellite preliminary budgets

Both system concepts (A and B) have very similar mass and power budgets. Due to the different pointing philosophies adopted, the mass distribution between instrument and platform differs slightly in the two concepts. Tables 6.2 and 6.3 summarise the estimated values, including a design margin in the individual values and indicating the system margin.

	Concept A	Concept B
Instrument	410	250
Platform	290	500
Dry mass	700	750
Fuel + Launch adaptor	50	50
System margin (10%)	75	80
Launch mass	825	880

Table 6.2: *Mass budgets for both concepts [kg].*

Instrument	320
Platform	270
Total	640 (including margin)

Table 6.3: *Power budget [W] (average over typical orbit).*

6.5 Mission and Operations Profile

The definition of the mission profile involved two aspects: the orbit selection and the mission planning and operations strategy. The selection of the orbit is mostly driven by three requirements: to provide the required access time of 3 days to the sites of interest, to optimise the directional sampling over these sites, and to favour if possible a lower altitude, beneficial for instrument radiometry and launch aspects. The baseline orbit chosen for the SPECTRA mission is a Sun-synchronous orbit with 14+9/14 revolutions per day (implying a 14-day repeat cycle), with a mean altitude of about 680 km. A dedicated mission simulator has been used to support the mission planning and operation strategy analyses.

A typical mission acquisition scenario has been elaborated, together with an input schedule for site acquisition. Figure 6.7 provides a graphical overview of such a request scenario for a full year.

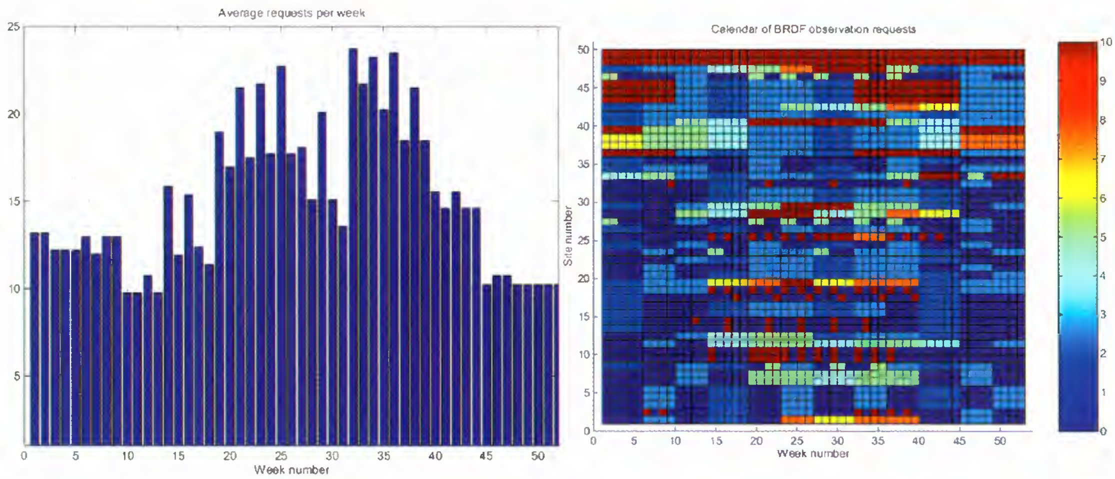

Figure 6.7: *Calendar of user requests. Left: average user requirements per week — right: expected frequency of observation per site (vertical axis) and per week (horizontal axis).The colour bar indicates the expected frequency of observations.*

A background planning of 14 days (the orbit cycle) is recommended, with possible updates and re-planning on a 3 day basis, to account for short-term evolutions.

The satellite must have the appropriate level of autonomy to relieve the ground controllers of a number of routine tasks and reduce manpower costs. This degree of autonomy is proposed as the baseline for the SPECTRA mission.

A typical orbital scenario is sketched in Figure 6.8, and it consists of the following phases:

BRDF sequence (1 to 3 per orbit)

¥ During such a sequence, the satellite acquires a series of 7 images according to the directional requirements. Such an acquisition sequence lasts for about 400 s. Each image acquisition lasts for about 20 s as follows :

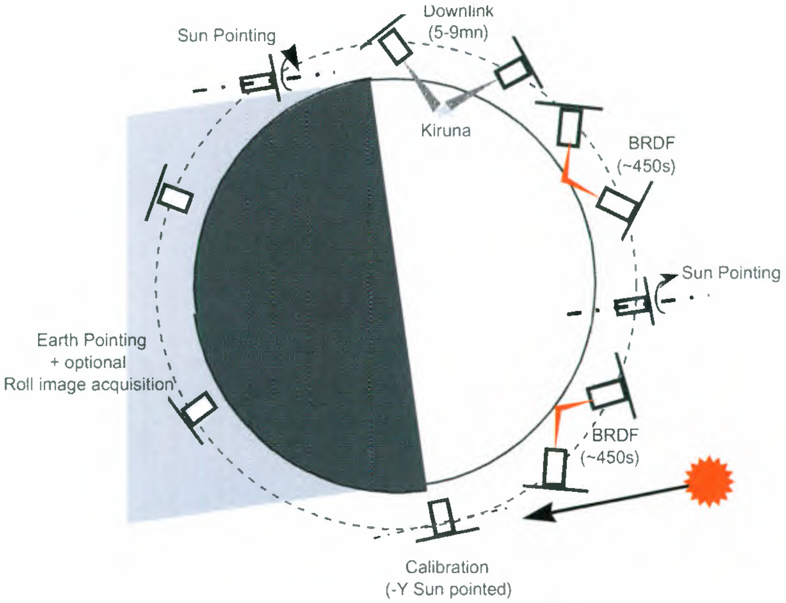

Figure 6.8: *A typical orbit scenario.*

- the first ten seconds are used for the thermal infrared relative spatial calibration, needed before each image for radiometric reasons,
- the last ten seconds are used for the image acquisition; a satellite slow down manoeuvre is applied so that this duration corresponds to a 50 km x 50 km image.

Sun pointing sequence

When the satellite is not in image acquisition mode, its attitude is set so as to ensure the best Sun illumination of the solar arrays, to charge the batteries,

Calibration sequence

Once per week, when passing above the southern orbital pole, the instrument is calibrated using Sun illumination of the diffusers. Whilst doing this, the satellite is in Earth pointing attitude; this sequence lasts about 2 minutes.

Eclipse sequence

During eclipses the satellite attitude remains in inertially pointed mode. If TIR imaging is requested, the satellite points towards the Earth.

Downlink sequence

During downlinking, the satellite attitude guarantees coarse pointing towards the station (a few tens of degrees).

6.6 Ground Segment and Data Processing

The ground segment comprises 4 major elements:

- the Command & Data Acquisition Element (CDAE): responsible for the TT&C links with the satellite and the acquisition of its scientific data.
- the Mission Operations and Control Element (MSCE): in charge of mission operations and satellite planning and control.
- the Processing & Archiving Element (PAE): in charge of further processing and quality control of the scientific data
- the Scientific Data Centre (SDC), which represents the user.

An overview of the ground segment is provided in Figure 6.9, with the main functions allocated to each element.

Figure 6.10 summarises the different processing steps up to Level-1b4.

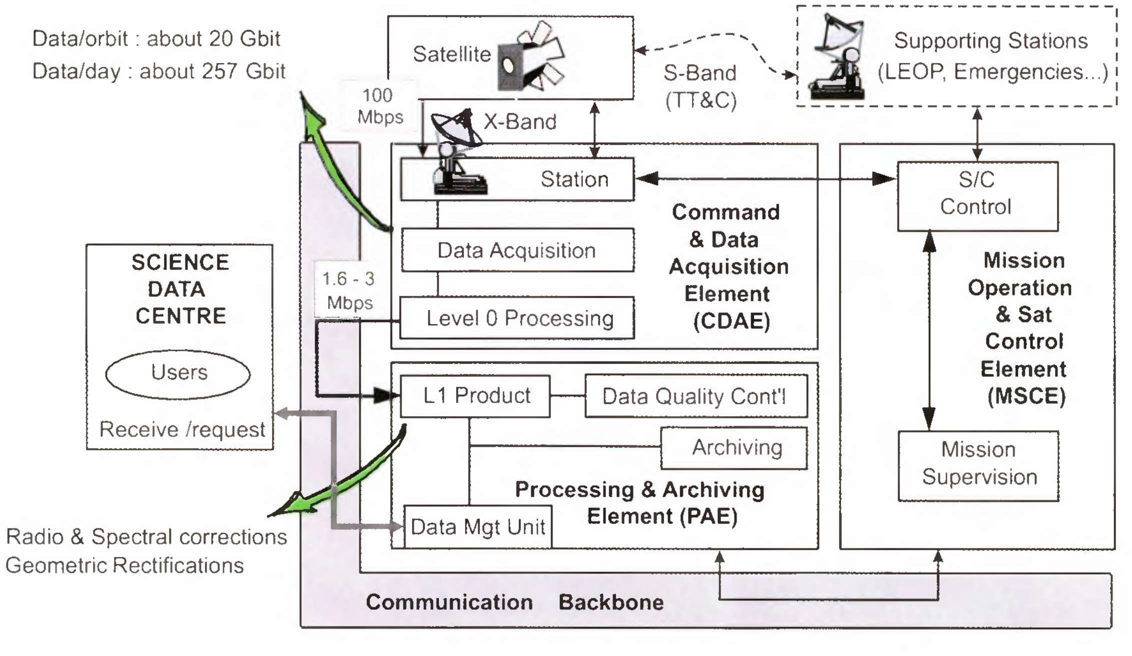

Figure 6.9: Overview of the SPECTRA ground segment.

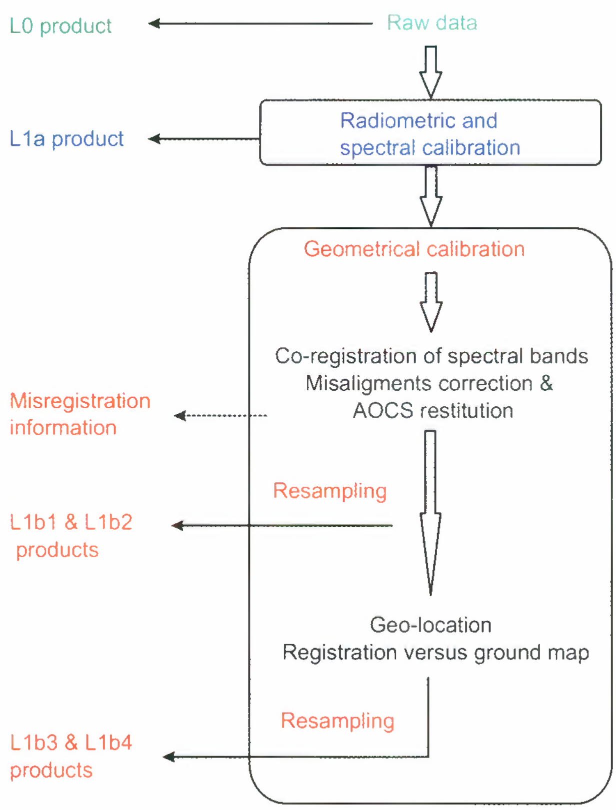

Figure 6.10: *SPECTRA processing levels.*

Table 6.4 gives the in orbit data characteristics. The numbers correspond to the nominal operational case of two full BRDF measurements per orbit, with a selection of 60 spectral bands. Different acquisition modes are possible (e.g. the acquisition of the full spectrum).

Image size	1250 x 1000 pixels (max)
Bit resolution	14 bit
Number of bands (nominal)	62
Number of angles	7
Number of BRDF sequences (average)	2
Number of blind orbits (max)	11
Compression (lossless)	1.8
Total	93 Gbit

Table 6.4: *SPECTRA data volumes and rates budget.*

With these values, a storage capacity of 100 Gbit on-board is compatible with the requirements, and a downlink capacity of 100 Mbit/s (standard X-band transmission) leads to a total downlink time of about 21 minutes, which is entirely compatible with a high latitude receiving station (such as Kiruna).

6.7 Launcher

The spacecraft concepts proposed for the SPECTRA systems are compatible with the Rockot launcher, as shown in Figure 6.11.

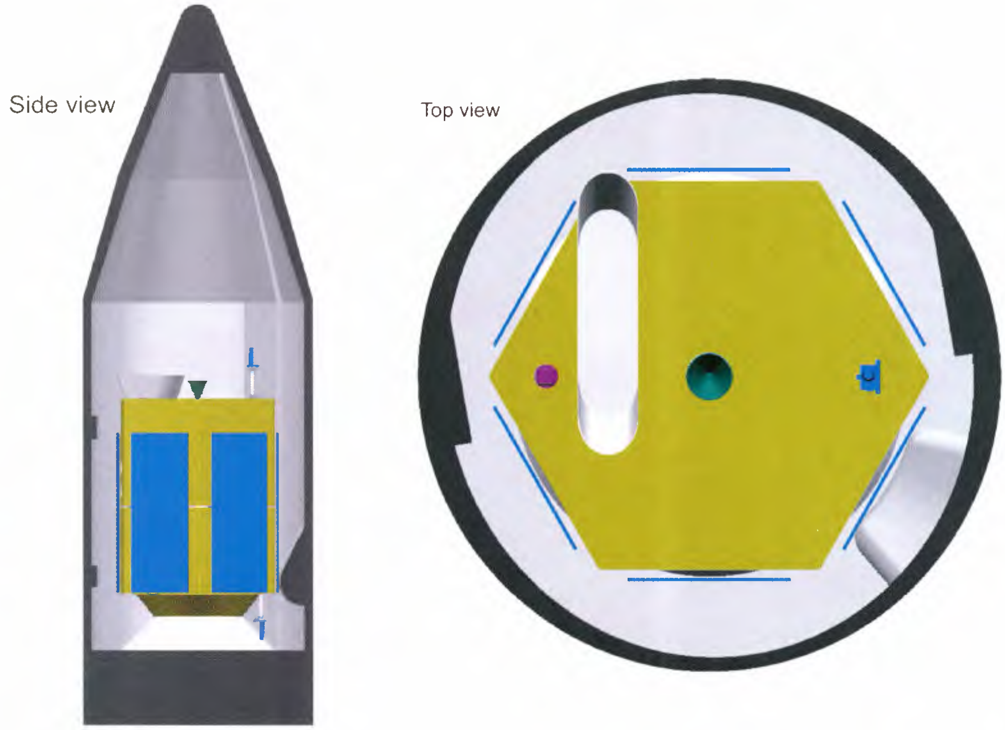

Figure 6.11: *Spectra spacecraft within Rockot.*

7 Programmatics

7.1 Introduction

This chapter briefly outlines the programmatic aspects of SPECTRA's implementation considering related international missions and constraints such as potential technical risks and development schedule. Section 7.2 presents the technical maturity, the heritage and the risk areas for the concepts developed in the pre-Phase A studies. Section 7.3 presents the international context and the related missions, both approved and planned. The contribution of SPECTRA to the enhancement of our Earth observation capabilities and its application potential are outlined in Section 7 .4.

7.2 Technical Maturity, Critical Areas and Risk

The technical maturity of the SPECTRA mission is consistent with a launch in 2008. This is based on the long experience accumulated in Europe in previous and current programmes, both at preparatory level (e.g. the HRIS, HRTIR and PRISM instruments, the LSPIM mission), as well as in terms of instruments/missions in orbit or about to fly (e.g. the MERIS instrument on Envisat, the CHRIS instrument on PROBA, the APEX airborne demonstrator). The platform has a strong heritage from the on-going Earth Explorers and other missions. No fundamentally critical items have been identified, either for the instrument or for the platform.

The clear separation of the platform and the (single) spectro-radiometer instrument and the background experience with the related ground processing permit the parallel development of instrument, platform and ground segment. The development risks are associated with two well-identified elements, namely the detectors and the control momentum gyros (CMG). For the SWIR detectors, the risk is being mitigated with the on-going ESA development of a hybrid HgCdTe-CMOS (CMT) detector array. A similar version of such a detector will be tested on the APEX airborne hyper-spectral demonstrator. For the TIR detection, CMT linear arrays have already been developed in Europe, but have shown poor yields for long arrays; the technological efforts should therefore be continued during Phase A. CMG have been baselined in one of the proposed satellite configurations and indicated as an option in the other. They will be used to meet the agility requirements with combined along- and across-track pointing. Although there is no current European off-the-shelf source, it is planned to develop CMG in the frame of national programmes and of coordinated ESA activities. First design assessments should be available towards the end of 2001.

Table 7.1 summarises the preliminary risk assessment for the most critical elements

Element	Implementation	Risk/Heritage
Detectors	• SWIR: HgCdTe CMOS 2-D array • TIR: HgCdTe CMOS linear array	• Development on-going • Performance demonstrated; specific development needed for the detector size required
Attitude Control Subsystem	Control Momentum Gyros (CMG)	Development on-going

Table 7.1: *Risk assessment for the key system elements.*

7.3 International Cooperation and Related Missions

Because of its expected role in collecting key information with which to understand the terrestrial ecosystems and their role in and response to climate changes, SPECTRA is clearly of global interest and can play a major role in the international effort to further our understanding of the biosphere. There is thus strong potential for scientific and technical international cooperation, with a good chance that SPECTRA might play a prominent role in the science underpinning the definition of global environmental policies. As already noted in Chapter 5, the field- and ground-segments of SPECTRA will have strong ties with the IGBP GCTE and BAHC programmes, as well as with WCRP GEWEX.

The missions most closely related to SPECTRA have been discussed in Chapter 5.

SPECTRA will also support and complement other missions aimed at observing land processes on different scales and in different regions of the electromagnetic spectrum, as well as missions addressing the atmospheric component of the carbon cycle.

7.4 Enhancement of Capabilities and Potential for Applications

The expected advances in science have been discussed in previous chapters. As shown there, this mission is also relevant to the enhancement of applications (such as land use observations, resource management and global carbon, energy and water budget estimates). The application potential of a mission like SPECTRA has been recognised for many years. As another product of the long optical remote sensing development effort in Europe, SPECTRA will extend and consolidate European expertise in the area of hyper-spectral instrumentation.

The data from SPECTRA will be fundamental to the interpretation and exploitation of data from future super and/or hyper-spectral missions. It will provide the knowledge base needed to develop space-based tools for long-term observations of the state and mechanisms of the biosphere, as required for the European GMES effort.

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Acronyms and Abbreviations

AATSR	Advanced ATSR
ACECHEM	Atmospheric Chemistry Explorer
AERONET	Aerosol Robotic Network
AirMISR	Airborne Multi-angle Imaging Spectro-Radiometer
AIRS	Atmospheric Infra-Red Sounder
ANN	Artificial Neural Network
AO	Announcement of Opportunity
AOCS	Attitude and Orbit Control System
APEX	Airborne PRISM Experiment
APU	Analogue Processing Unit
ASAS	Advanced Solid-state Array Spectro-radiometer
ASI	Agenza Spaziale Italiana – Italian Space Agency
ASTER	Advanced Spaceborne Thermal Emission and Reflection radiometer
ATSR	Along Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
BAHC	Biospheric Aspects of the Hydrological Cycle (Core Project of IGBP)
BigFoot	Project to validate MODIS terrestrial ecology data products
BOREAS	BOReal Ecosystem-Atmosphere Study
BRDF	Bi-directional Reflectance Distribution Function
BRF	Bi-directional Reflectance Factor
BSM	Bus Service Module
BTDF	Bidirectional Temperature Distribution Function
CCD	Charge-Coupled Device
CCU	Cryocooler Control Unit
CDAE	Command & Data Acquisition Element
CEOS	Committee on Earth Observation Satellites
CERN	China's Ecosystem Research Network
CHRIS/PROBA	Compact High Resolution Imaging Spectrometer/ PRoject for On-Board Autonomy
CMDL	Climate Monitoring and Diagnostic Laboratory
CMG	Control Momentum Gyros
CMOS	Complementary Metal Oxide Semiconductor
CMT	Cadmium Mercury Telluride (detectors)
CNES	Centre National d'Etudes Spatiales
DAIS	Digital Airborne Imaging Spectrometer
DAISEX	DAIS EXperiment
DEM	Digital Elevation Model
DGVM	Dynamic Global Vegetation Model

DH&C	Data Handling and Control
DTM	Digital Terrain Model
EarthCARE	Earth Clouds Aerosol and Radiation Explorer
ECMWF	European Centre for Medium-Range Weather Forecasting
ESM	Earth System Model
ETM	Enhanced Thematic Mapper
Eumetsat	European Organisation for the Exploitation of Meteorological Satellites
EUROFLUX	A project financed by the European Commission to study carbon and water fluxes in the environment along a north-south transect
FAO	Food and Agriculture Organization
fCover	Fractional vegetation cover
FIFE	First ISLSCP Field Experiment
FPA	Focal Plane Array
fPAR, fAPAR	Fraction of absorbed photosynthetically active radiation
FWHM	Full Width at Half Maximum
GAIM	Global Analysis Interpretation and Modelling
GAW	Global Atmospheric Watch
GCM	Global Circulation Model, Global Climate Model
GCOS	Global Climate Observation Strategy
GCTE	Global Change and Terrestrial Ecosystems
GCTE	Global Change and Terrestrial Ecosystems
GEMI	Global Environment Monitoring Index
GEWEX	Global Energy and Water Cycle Experiment
GLI	GLobal Imager
GMES	Global Monitoring of Environment and Security
GOOS	Global Ocean Observation Strategy
GPP	Gross Primary Productivity
GSFC	Goddard Space Flight Center
GTOS	Global Terrestrial Observation Strategy
HAPEX	Hydrology-Atmospheric Pilot Experiment
HRIS	High Resolution Imaging Spectrometer
HRTIR	High Resolution Thermal Infrared Radiometer
HRV	High Resolution Visible
HYMAP	HYperspectral MAPping
HyPSEO	HyPerSpectral Earth Observation
ICSU	International Council of Scientific Unions
ICU	Instrument Control Unit
IGBP	International Geosphere Biosphere Programme
IGFA	International Global-change Funding Agencies
IGOS-P	Integrated Global Observing Strategy Partnership
IHDP	International Human Dimensions Programme
INRA	Institut National de la Recherche Agronomique
IOC	Intergovernmental Oceanographic Commission

IPCC	Intergovernmental Panel on Climate Change
ISLSCP	International Satellite Land-Surface Climatology Project
JGOFS	Joint Global Ocean Flux Study
JPL	Jet Propulsion Laboratory
JRC	Joint Research Centre
LAD	Leaf Area Distribution
LAI	Leaf Area Index
LBA	Large-scale Biosphere atmosphere experiment in Amazonia
lidar	light detection and ranging
LIDF	Leaf Inclination Distribution Function
LSE	Land Surface Experiment
LSM	Land Surface Model
LUT	Look-Up Table
MEDEFLUX	A project financed by the European Commission to study carbon and water fluxes in the environment along the Mediterranean coast
MEP	Mission and Experiment Plan
MERIS	Medium Resolution Imaging Spectrometer
Meteosat	Meteorological Satellite, a geostationary platform operated by Eumetsat
MISR	Multi-angle Imaging SpectroRadiometer
MLI	Multi Layer Insulation
MMU	Mass Memory Unit
MODIS	Moderate Resolution Imaging Spectrometer
MRPV	Modified Rahman Pinty Verstraete model
MSCE	Mission operations and Satellite Control Element
MSG	Meteosat Second Generation
NASA	National Aeronautics and Space Administration
NBP	Net Biome Productivity
NDVI	Normalized Difference Vegetation Index
NEdr	Noise Equivalent delta reflectance
NEdT	Noise Equivalence difference Temperature
NEE	Net Ecosystem Exchange
NEP	Net Ecosystem Productivity
NIR	Near-InfraRed
NOAA	National Oceanographic and Atmospheric Administration
NPP	Net Primary Productivity
NWP	Numerical Weather Prediction
PAE	Processing and Archiving Element
PAR	Photosynthetically Active Radiation
PARCINOPY	A ray-tracing model of RT developed at INRA
PLM	PayLoad Module
POLDER	POLarization and Directionality of the Earth's Reflectance

PRISM	Processes Research by an Imaging Space Mission (the Space Segment design of the former Land Surface Processes and Interactions Mission concept)
PROMET	PRocess-Oriented Multiscale Evapo-Transpiration model
RPV	Rahman Pinty Verstraete model
RT	Radiation Transfer
SAIL	Scattering by Arbitrarily Inclined Leaves model
SAVI	Soil-Adjusted Vegetation Index
SDC	Scientific Data Centre
SeaWiFS	Sea-viewing Wide Field of view Sensor
SEBI	Surface Energy Balance Index
SEVIRI	Spinning Enhanced Visible and InfraRed Imager
SMOC	SPECTRA Mission Operations Centre
SMU	Satellite Management Unit
SPECTRA	Surface Processes and Ecosystems Changes Through Response Analysis
SPG	Scientific Preparatory Group
SPOT	Système Probatoire d'Observation de la Terre
SSI	Spatial Sampling Interval
SVAT	Soil Vegetation Atmosphere Transfer
SWIR	Short Wave Infra-Red (1300 – 2500 nm)
TCO	Terrestrial Carbon Observation
TIR	Thermal Infra-Red
TM/TC	Telemetry and Telecommand
TOA	Top Of the Atmosphere
TOPC	Terrestrial Observation Panel for Climate
TT&C	Telemetry Tracking and Command
UN	United Nations
UNEP	UN Environment Programme
UNESCO	UN Educational, Scientific and Cultural Organization
UNFCCC	UN Framework Convention on Climate Change
VCL	Vegetation Canopy Lidar
VEGETATION	Name of an instrument on the SPOT-4 platform, operated by CNES
VIS	Visible
VNIR	Visible and Near-Infrared
WALES	WAter vapour Lidar Experiment in Space
WATS	WAter vapour and temperature in the Troposphere and Stratosphere
WCRP	World Climate Research Programme
WMO	World Meteorological Organization

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