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REPORTS FOR ASSESSMENT

THE NINE CANDIDATE EARTH EXPLORER MISSIONS

Land-Surface Processes and Interactions Mission

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THE NINE CANDIDATE EARTH EXPLORER MISSIONS

Land-Surface Processes and Interactions Mission

ESA SP-1196 (2) – The Nine Candidate Earth Explorer Missions –
LAND-SURFACE PROCESSES AND INTERACTIONS MISSION

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1. Introduction

For the post 2000 time frame two general classes of Earth Observation missions have been identified to address user requirements, namely:

Earth Explorer Missions – these are research/demonstration missions with the emphasis on advancing understanding of the different Earth system processes. The demonstration of specific new observing techniques would also fall under this category.

Earth Watch Missions – these are pre-operational missions addressing the requirements of specific application areas in Earth observation. The responsibility for such missions would eventually be transferred to operational (European) entities and to the private sector.

Nine Earth Explorer missions have been identified as potential candidates for Phase A study. For each of these candidate missions Reports for Assessment have been produced.

This particular Report for Assessment is concerned with the Earth Explorer Land-Surface Processes and Interactions Mission. It has been prepared by one of the nine Mission Working Groups that have been established to produce these Reports. The four (external) members of this particular Mission Working Group are F. Baret (INRA, France), R. Gurney (University of Reading, UK), M. Menenti (Winand Staring Centre Wageningen, The Netherlands) and M. Verstraete (JRC, Italy). They were supported by members of the Agency who advised on technical aspects and took the lead in drafting technical/programmatic sections. This Report, together with the other eight candidate Earth Explorer missions, is being circulated amongst the Earth Observation research community in anticipation of a Workshop which will be held in Spain in May 1996.

Several issues of concern to mankind including the effect of increased CO_2, loss of biodiversity, pollution and the pressure of mankind on natural resources partially drive the climate change. Possible human induced climate changes enhance climate variability, which affects eco- and production systems in a complex way. A better understanding of both biospheric processes and of the resilience of production systems is a pressing need.

The objective of a mission dedicated to the study of land-surface processes and their interactions is to enhance the capability to model these processes, changes and interactions by advancing, understanding and characterisation of processes through accurate and robust observations. An improved understanding of the relevant processes at small length scales will complement in essential ways that already acquired at larger scales; the capability to observe the Earth surface with a range of instruments and at a variety of spatial resolutions is expected to result in major advances in environmental monitoring and management.

All the Reports for Assessment follow a common general structure comprising seven chapters. They start by addressing the scientific justification for a particular mission and move on to detail its specific objectives. This is followed by detailing the specific observation requirements and a listing of the various mission elements needed to satisfy the observational requirements. Then consideration is given to the implications of meeting the observational requirements in terms of both the space and ground segment as well as requisite advances in scientific algorithms and processing/assimilation techniques. Finally programmatic aspects are considered.

2. Background and Scientific Justification

2.1. The Issues

A number of human activities contribute directly or indirectly to possible changes in the Earth's climate. The most often quoted example is the steady increase in atmospheric CO_2 caused by fossil fuel burning, which it is believed may lead to a progressive warming of yearly average temperatures near the ground, especially in mid and high latitudes. The adverse effects of this temperature increase are widely predicted to include increased variability in weather systems (more floods, more droughts), disruption to water systems leading to conflict over supplies and salinisation of soils, greater stress on ecosystems leading in cases to desertification, and perhaps an increase in the extent and frequency of diseases such as malaria. It is not only through changes in atmospheric composition that human activity leads to climatic perturbation. The land surface is largely responsible for the forcing of the atmosphere at a wide variety of spatial and temporal scales, through topography and the diversity of surface types, each with its own mechanical and thermal properties. Major changes in land cover, brought about by agricultural and industrial activities, may therefore affect climate through changes to the pertinent physical characteristics. The latest issue of the Intergovernmental Panel on Climate Change (IPCC) Report (1995) strongly suggests that human activities may have already resulted in measurable changes of climate.

Foreseeable changes in climate may result in potentially significant impacts on the biosphere itself. A global increase in temperature, and changes in patterns of precipitation, may be expected to affect the functioning of natural and managed ecosystems, and perhaps more importantly, in terms of social and economic consequence, their spatial distribution. Shifts of climatic zones may occur at rates faster than the capability of affected biomes to adapt. Changes in temperature and atmospheric composition may also be expected to lead to significant changes in the rates at which carbon and other nutrients are cycled through ecosystems; for example, acid rain depositions may seriously affect the ability of boreal forests to absorb carbon from the atmosphere. Environmentally useful or economically desirable consequences may also result from climatic changes, and these will need much attention to prevent abuse of new resources and manage fragile environments during a delicate transition phase.

Thus changes to the composition of the land surface can lead to changes in the patterns of climate, and changes in climate lead to changes in the workings of the biosphere. It is an urgent matter to understand how the biosphere may evolve in response to climate changes in order to be able to predict adverse impacts, and to prepare appropriate policy measures for their mitigation.

In the document 'Reducing Uncertainties' (IGBP, 1992), six questions are posed, each to be addressed by one of the core projects of IGBP. The ones most relevant to land-surface processes and their interactions with the atmosphere and the climate system are:

1) How is the chemistry of the global atmosphere regulated, and what is the role of biological processes in producing and consuming trace gases?
3) How changes in land use affect the resources of the coastal zone, and will changes in sea level and climate alter ecosystems?
4) How does vegetation interact with physical processes of the hydrological cycle?
5) How will global changes affect terrestrial ecosystems?

Elsewhere in the report other questions linked to those above are posed:

- How do land use changes affect the resources of the ecosystem?
- What are the fluxes to and from major carbon reservoirs?

These questions can only be answered when there is an adequate scientific comprehension of the biological and physical processes and interactions occurring at the Earth's surface, and of land surface interactions with other components of the biosphere.

It is to address these issues, that the Land-Surface Processes and Interactions Mission (LSPIM) has been conceived.

2.2. Scientific Background

2.2.1. Observations and Modelling of Land Surface – Atmosphere Interactions and Ecosystems

General Circulation Models

The only significant source of energy for all living and non-living processes on Earth is the radiation provided by the sun. On average, about one third of this energy is reflected to space by the clouds, the atmosphere and the surface; the other two thirds are used to heat the planet, to generate the air and ocean currents, etc. A small fraction (much less than 5%) is stored as chemical energy in the form of complex carbon-based molecules through the process of photosynthesis, and serves to maintain all other biological processes in plants, animals, and humans. It is therefore of the utmost importance to estimate how much of this radiation is available, how it is stored, when it is released, how it is used, etc.

Fluxes between vapour, liquid and solid phases of water are intimately coupled to exchanges of energy between the surface and the atmosphere. These fluxes strongly affect many aspects of the climate system through such mechanisms as cloud and precipitation formation, or albedo modifications. The availability of water largely controls the nature and extent of biomes, while excessive or deficient water amounts create havoc in natural and managed ecosystems alike. Accurate observations and modelling of these processes at large length scales require accurate sampling at the length scales relevant for land-surface processes; this cannot be done without observations of the variables directly linked with net radiation and its allocation at relatively high spatial resolutions. Further research is needed especially to improve the estimation of these fluxes on the basis of environmental variables which are easier to observe, and over areas of the order of hundreds to thousands of square kilometres typical of the grid size of climate models.

Vegetation cover constitutes the bulk of the biosphere, and exchanges very large amounts of carbon with the atmosphere. This influence is noticeable in the seasonal variations of the chemical composition of the atmosphere. A major issue of current interest is the question of the so called missing sink of carbon, since a large fraction of the carbon dioxide emitted into the atmosphere through various human activities and natural processes cannot be accounted for by the estimated carbon flux into the upper ocean and the observed increase in atmospheric CO_2 concentration. A net assimilation into the biosphere greater than what is currently being estimated is postulated, but detailed studies need to be carried out to better understand where and how this carbon is accumulated. Improved knowledge on the fate of carbon in the environment is urgently needed to predict the likely climatic changes and assess the most efficient ways to prevent or adapt to their consequences. A number of other biogeochemical cycles affecting the distribution of the surface environment and of the ecosystems have been identified. These include the cycling of nitrogen, sulphur, phosphorus, and other elements critical to many living organisms. In all these cases, the state of the art is much less advanced than for the water or energy cycle. Ecosystem modelling requires knowledge of many variables that drive the functioning of vegetation and soils and their energy and mass exchanges with the atmosphere.

The dynamics of the biosphere are extremely complicated, and sophisticated models are required to describe it. A basic tool for analysis of the global Earth-Atmosphere System is provided by General Circulation Models (GCMs), and global models of the biosphere and hydrosphere have recently started to be developed. GCMs are essentially the same models that are used for Numerical Weather Prediction (NWP); indeed, the United Kingdom Meteorological Office uses exactly the same code (the 'Unified Model') for both NWP and climate research. GCMs consider patterns of climate over the whole globe, and are limited in the spatial resolution at which they operate. Grid cells of 100 km by 100 km are typical at the moment, but some models have finer resolution grids, down to 50 km by 50 km in some locations, and one can expect models to be operating at this finer level in the post 2000 time frame. Even the smallest model grid size is much larger than the length scale of the relevant biophysical processes.

Among the limitations to the accuracy of the predictions of GCMs and climate models three are particularly relevant to the characterisation of surface processes and the interactions of terrestrial environments with the atmosphere:

1) The nature and state of the surface, and in particular its influence on the exchanges of energy, momentum and mass with the atmosphere, must be better taken into account to estimate the evolution of the atmosphere, on time scales of a few days or more.
2) The strong dependence of weather and climate on the initial conditions may limit the predictability of the atmosphere to at most two weeks, except for long term statistical averages at frequencies corresponding to periodic forcing (e.g., seasons).
3) The necessity to model the dynamics of vegetation when subjected to climatic changes on long term ranges.

The importance of the land surface-atmosphere interaction and the associated feedback depend on the time scale of the model. For short range (hours) NWP, influences by the surface are of a minor relevance, for medium range analysis (days) simplified representations of the surface are adequate. For decadal time scales climate models, surface parameterisations including the proper dynamics and feedback become very important because surface processes largely control the partitioning of the energy available to the entire climate system. In fact, when dealing with the long term climatic changes of the past (e.g., ice ages, etc.) the state of the surface and its control of the energy and water cycles are perhaps the principal climate drivers.

The sensitivity of GCMs to the representation of land-surface processes was emphasized in 1981 at a seminal meeting held by a working group of the JSC/WCP in Greenbelt, Md. (Eagleson, 1981). At that time GCMs used a rather simple parameterisation of land surface hydrology developed by Manabe (1969) and based on earlier work by Thornthwaite and Mather (1955) and Budyko (1956); see also Sellers (1969). Land surface hydrology was basically reduced to include a soil water reservoir, assumed to be identical (i.e. water storage capacity independent of soil type, depth, etc.) everywhere in the world. Even this "stone-age" land surface model, however, was sufficient to show that soil water content had a very significant effect on the allocation of net radiation into sensible, latent and soil heat flux and, therefore, on atmospheric processes (Mintz, 1982; Rowntree and Bolton, 1983). Particularly,the soil moisture boundary condition had a considerable influence on medium-to-long range weather forecasts and simulated monthly mean climatic states.

From the very beginning it was realized that land-surface processes had to be modelled in a more realistic way; however, this came with a problem: how could solutions of varying complexity be evaluated by means of experiment? The proposed land surface parameterisations drew heavily from simultaneous developments in micrometeorology and ecology, and models could be evaluated experimentally when applied to well defined systems and at small length scales. The resulting Land Surface Models (LSM) were to be used within GCM's at much larger length scales, however, and the experimental challenge was clearly perceived. One strategy suggested for validation of GCMs was by comparison of GCM-water balances with calculations done by means of watershed hydrological models. This led to conceive detailed procedures for a standard Hydrologic Atmospheric Pilot EXperiment (HAPEX) in the early 80's. In the already mentioned report by Eagleson (1981) the sensitivity of GCMs to other land surface properties was stressed: snow cover, soil temperature and soil heat storage, albedo, emissivity, surface roughness and vegetation. It can be concluded that already in 1981 there was a consensus in the scientific community that the land surface was a relevant climate factor and that better LSMs had to be integrated with GCMs. Future efforts had to be dedicated to concurrent improvements in modelling concepts, tools and in observational capabilities of the parameters controlling the fluxes of energy, water and momentum into and from the atmosphere (Eagleson,1981).

Most of the theoretical and experimental knowledge gathered in the 60's and 70's over energy and water fluxes between the Earth and the atmosphere apply to horizontally homogeneous land surfaces. Mean turbulent fluxes are not constant with height over heterogeneous land surfaces and no simple relationships between fluxes and vertical gradients applies. The development of experimental and theoretical approaches to deal with these coupled horizontal and vertical heterogeneities became the focus of research on land-surface processes .

In recent years a growing consensus has been reached (e.g. In the IGBP core project on Global Analysis, Interpretation and Modelling – GAIM) on the need of improving GCMs by including global ecosystems models interacting with the atmosphere and hydrological processes. Ecosystems models span the full range of scales between point processes and GCM grid cells. Ecosystems also form a much more natural domain for the modelling of a lumped surface response. The effects of climatic change are felt at this level, and so impacts can only be sensibly predicted for entire ecosystems. Ecosystems are also the most appropriate theatre within which to model biogeochemical cycling on land. The further development of models of ecosystem functioning and evolution is therefore essential to a full understanding of the feedbacks of vegetation on climate, to predicting the impact of climate change on the carbon cycle for instance, and to assessing the likely consequences of different environmental strategies and policies. In particular, there is a pressing need for coupled ecosystem-climate models, at all ecosystem scales, and for data to serve these models. The IGBP Core Project Global Change Terrestrial Ecosystems (GCTE) is currently promoting the development of dynamic vegetation models, precisely for studying climate impacts on ecosystems. Over the last decennia rapid developments have occurred in local agro-meteorological models enabling applications for productivity assessment at regional and continental scales. The accuracy of these models could be significantly enhanced by improved description of the elementary processes and their interactions.

Transfer of Knowledge from Local to Global Scales

The spatial variability of land surfaces is high, and to study the processes involved, observations at the intermediate scale of few tens of metres are needed to form the link between what is verifiable locally and regional and global data sets. These data would be used as inputs to upscaled/aggregated land-surface processes models filling the gap between locally verifiable models and global land-surface processes models combined with GCMs. For upscaled/aggregated land-surface processes models such as Soil-Vegetation-Atmosphere Transfer models (SVATs) there are currently no appropriate measurements from satellites available. The spatial and temporal context of the Earth Explorer Land Surface Processes and Interactions Mission is displayed below.

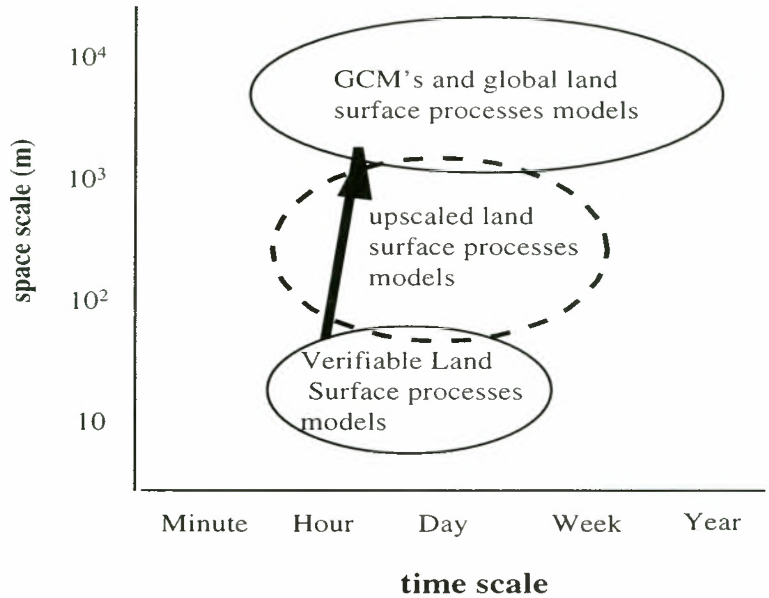

Figure 2.1. *Spatial and temporal context of the Land-Surface Processes and Interactions Mission*

The basic functioning of the land surface is described by (relatively) simple equations defining the physical processes at a point. These include the energy and mass fluxes which are among the most important surface-atmosphere interactions. Both numerical weather prediction models and GCMs describe land atmosphere interactions using one-dimensional parameterisations applied to each grid unit. Recent literature (e.g: Blyth and Dolman, 1995) indicates that Land-Atmosphere interactions are at least two dimensional due to spatial heterogeneity. This is the core challenge in the evolution from local to global models. Some means must be found of approximating actual processes and interactions with simplified formulations (parameterisations). The modelling and observing activities should proceed together and be coordinated, so that the models can be used to specify the most efficient observational sampling strategy. The measurements, in turn will help constrain and evaluate the models.

The study of land surface parameterisations is an active research area (Henderson-Sellers et al., 1993, Henderson-Sellers et al., 1995). A number of large scale experiments have been carried out under the auspices of various international agencies to try to attack the problem (table 2.1).

Experiment	Field Phase	Location-Area Covered (km × km)	Focus	References
HAPEX-Mobilhy	1986	SW France 100 × 100	water & energy	Schmugge & Andre (1991)
LOTREX-HIBE	1988,1990	Hildesheimer Borde 10 × 10	water & energy biometeorology	Jochum et al (1990)
FIFE	1987,1989	Kansas 10 × 10	water & energy remote sensing	Sellers & Hall (1992), Hall& Sellers (1995)
MONSOON-90	1990,1991	Arizona 15 × 10	water & energy remote sensing	Kustas & Goodrich(1994)
HEIFE	1991-1995	Heille basin China 70 × 90	water & energy	Wang et al (1994)
KUREX	1988	Kursk Russia 100 × 100	water & energy, remote sensing	
EFEDA	1991	Spain 85 × 130	Land degradation, biometeorology, remote sensing	Bolle et al (1993)
HAPEX-Sahel	1992	Niger 100 × 100	biometeorology, remote sensing	Goutorbe et al (1994)
NOPEX	1993-1994	Scandinavia	biometeorology, remote sensing	Lundin & Halldin (1994)
BOREAS	1993-1994	Canada 1000 × 1000	biometeorology, remote sensing	Hall & Sellers (1993)
GCIP	1995-2000	Mississippi Basin 2000 × 200	meteorology& remote sensing	IGPO (1992)
GAME	1998-1999	Eastern Asia	hydrology, meteorology	JSC (1994)
MAGS		Canadian Arctic basin MacKenzie basin	hydrology, climate impact	JSC (1994)
AMAZON (LAMBADA-BATERISTA	1998-2000	Amazon Basin 3000 × 2000	biometeorology, remote sensing	Sellers et al (1993)

Table 2.1. *International field experiments designed to study land surface process studies at large scales*

Each single experiment described in table 2.1 typically involved some 100 scientists, and huge amounts of ground-based and remote sensing data were collected during short periods of time.

The general philosophy of such an experiment is illustrated in figure 2.2. The link between the point process measurements and the coarse resolution observations are shown in figure 2.2 as being obtained from aircraft, but high resolution satellites were also used at the intermediate level.

First results of the first experiments have already been published in the scientific literature (Schmugge and Andre, 1991; Sellers and Hall, 1992; Mitsuta, 1994; Sorooshian and Gurney, 1994).

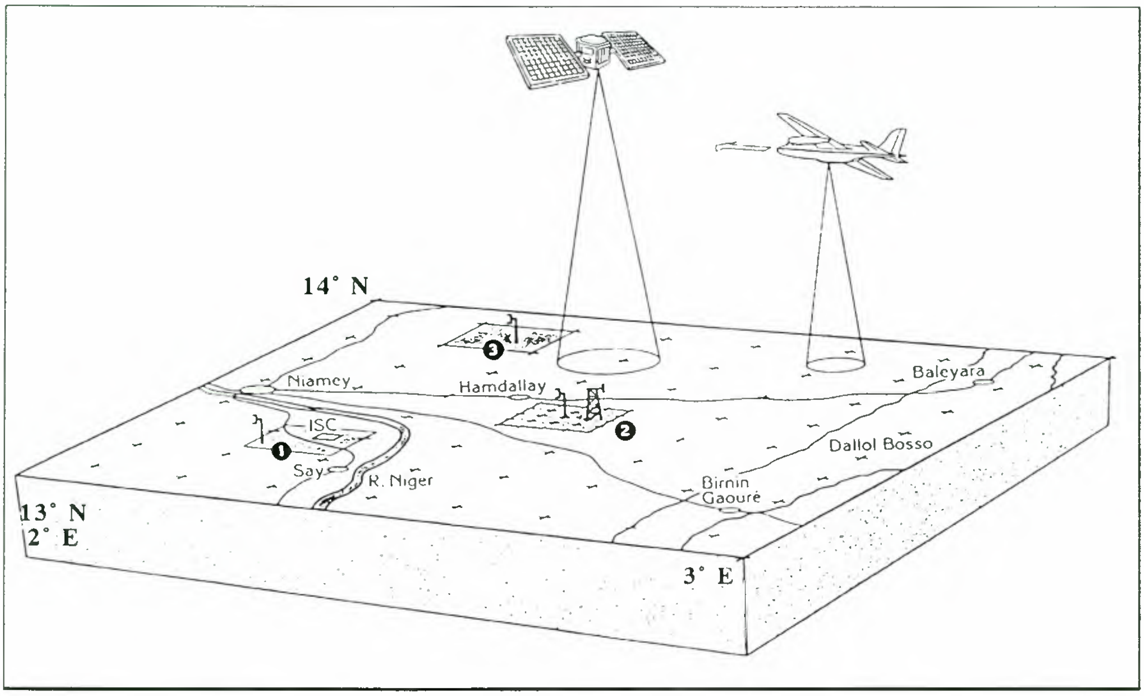

Figure 2.2. *The experimental scheme for HAPEX Sahel showing the location of the three intensively monitored super sites*

It is expected that experiments of this kind will continue in the post 2000 time frame. Where the experiments listed in table 2.1 used satellite data, these were derived from instruments which had not been designed for the purpose of improving process modelling. This led to accept empirical and approximate solutions because of shortcomings in the available measurements. In order to reduce uncertainties in understanding and modelling of interactions and processes the availability of more accurate and physically based satellite observations would be an indispensable asset. The transfer from local to global observations and models appears therefore to be one of the main issues to be solved. This problem is relevant for energy, water and biochemical fluxes studies.

2.2.2. Energy and Water Fluxes

Soil water controls the allocation of energy at land surfaces at all scales as described in 2.2.1 through a complexity of hydrological processes (figure 2.3) which lead to complex spatial patterns of soil moisture and related land surface properties such as vegetation cover and albedo. To describe land atmosphere interactions one needs to observe and model the really integrated fluxes: when this is done using small grid size these complicated patterns are reproduced precisely and the area integration is accurate. With increasing grid size, e.g. as required to describe land - atmosphere interactions in GCMs and NWPs, it becomes increasingly difficult to reproduce the patterns at heterogeneous land surfaces precisely. It is therefore necessary to understand how to estimate the area integrated heat and water fluxes using observations at different resolutions. This will eventually lead to robust approaches to describe processes having relatively small length scales using aggregated models which parameterise interactions using effective land surface properties and fluxes which are defined below.

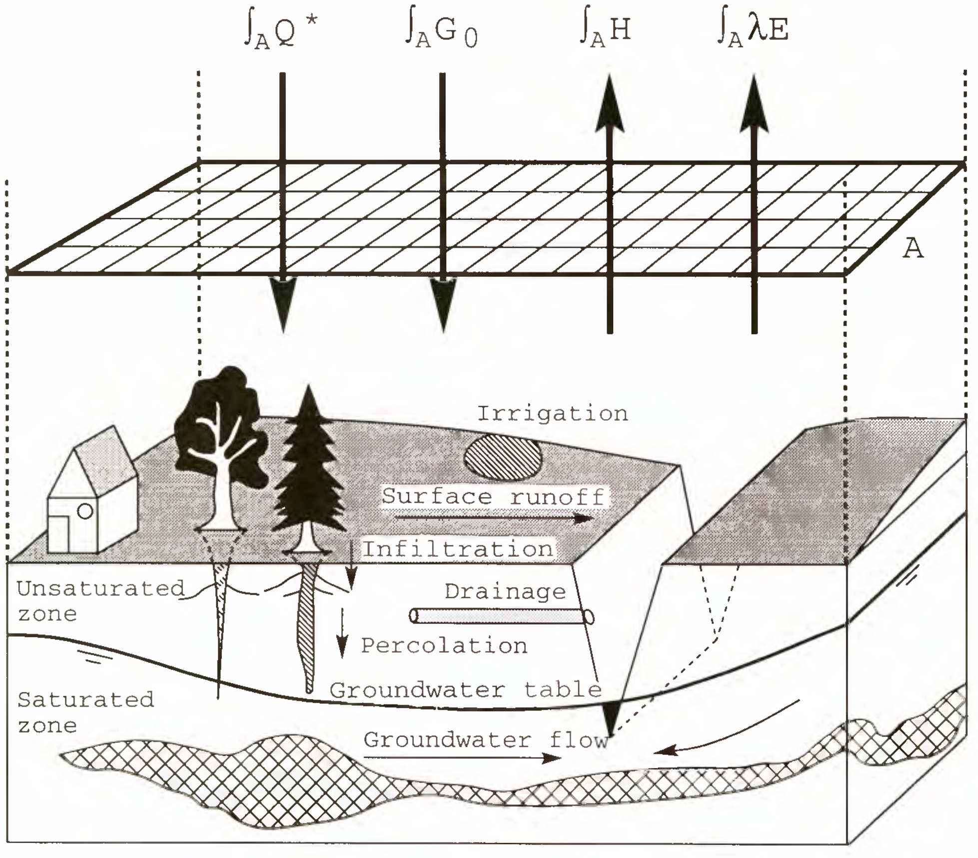

Figure 2.3. *Sketch Diagram describing hydrological processes and the area integration procedures of heat and water fluxes*

To establish a relationship among heat and water fluxes at heterogeneous land surfaces, we have three different possibilities:

a) at-surface heat balance equation

$$Q^* + G + H + \lambda E = 0$$

where Q^* is net radiation, G soil heat flux, H sensible heat flux and λE is latent heat flux, amount of energy required in the liquid-to-vapour transition of E (kg m^{-2} s^{-1}) of water.

b) water balance equation of a soil column

$$P + I + Q + d_m + d_w + E = 0$$

where P is precipitation, I is capillary rise or percolation, Q surface runoff, d_m change in soil water storage, d_w change in snow water equivalent and E is evaporation.

c) water balance equation of an atmosphere column

$$\frac{\partial w}{\partial t} + \frac{\partial q_v}{\partial x} = E - P$$

where ∂_w/∂_t is the time rate of change in precipitable water and $(\partial q_v/\partial x)$ is horizontal divergence of vertically integrated vapour flux.

The amount of water evaporated at the surface per unit time (E) appears in all three equations; the only link with the heat fluxes is given by equation (a): as emphasized above, land surfaces affect atmospheric processes precisely through the way hydrological processes shape patterns of soil water availability and eventually the allocation of net radiation. This implies that understanding land surface - atmosphere interactions require knowledge of all terms in the heat balance equation; surface temperature is determined by the relative magnitude of these fluxes and, therefore, must also be determined to describe the state of the land surface.

Moreover, in eq. (b) runoff and percolation are not accessible with space borne observations and, even though eq. (c) involves quantities observable with space borne sensors at least in principle, measurements would be feasible at very low resolution only and not useful to further our understanding of land surface - atmosphere interactions.

So, further studies of land - atmosphere interactions should use eq. (a) as a starting point and conceptual framework.

2.2.3. Biogeochemical Fluxes

Primary productivity is the most important mechanism by which vegetation defines and changes the physical characteristics of the Earth's surface such as albedo or roughness, also constitutes an active interface between soils and atmosphere. In this way it regulates not only CO_2 fluxes but also water, and more generally the cycling of biogeochemicals. Primary productivity results from the photosynthetic activity that transforms the light intercepted by the canopy into chemical energy. It is a function of elementary processes that are directly or indirectly linked to canopy biochemistry.

1) Light interception efficiency is the fraction of light intercepted by active green parts of the canopy determines the energy potentially available for photosynthesis. Light interception efficiency, the fraction of light that is intercepted by photosynthetically active elements of the canopy, is primarily governed by canopy structure that is mainly governed by the species, the phenological stage and the physiological status of the vegetation. Light interception efficiency is also critical for the water balance since it determines the partition of the radiative energy available for canopy transpiration and soil evaporation. Last, the light interception efficiency is also closely connected to the rain interception efficiency used for modelling canopy water balance.

2) Photosynthesis is the process by which photosynthetically active radiance (PAR) intercepted by the canopy is transformed into assimilates. This activity depends strongly on many factors directly or indirectly linked to the amount of chlorophyll in the leaf, the nitrogen and water status of the plants. It also depends strongly on temperature and atmospheric CO_2 concentration. Further, the rate of conversion of the light energy stored as chemical bonds into a given mass of final products (proteins, lignins, lipids, starch,..) depends obviously on the biochemical composition of the organs.

3) Stomatal resistance regulates the amount of water transpired by the leaves. It also directly determines the photosynthetic activity through the regulation of CO_2 exchanges at leaf surface level. For a given species, stomatal resistance depends on the water status of plants, light climate, and temperature. Canopy roughness depending on canopy structure constitutes an additional resistance to water and CO_2 exchanges from the leaf to the boundary layer.

4) Allocation is the process of partition of assimilates between the several types of organ to build structure (for light interception), storage and reproductive organs, and the roots (for water and nutrient uptake). Allocation is a critical element in the canopy functioning models. It depends on the species, the phenological stage and the physiological status of the vegetation. The role of water and nitrogen is also very important in the control of assimilates partitioning.

5) Respiration is the process by which canopy maintains its structure and grows. It is also releases CO_2 to the atmosphere. Respiration depends obviously on the amount, structure

and on the biochemical composition of canopy materials; it also depends strongly on temperature.

6) Senescence constantly modifies canopy structure. It depends strongly on temperature and light. Senescence eventually provides materials to litters and soils that is the main way of biogeochemical cycling at the very local scale.

7) Litter decomposition. The senescent material left over the soil constitutes the litter. This organic material decomposes gradually at a rate that depends on temperature, humidity and also strongly on its biochemical composition. The presence of compounds such as lignin that are difficult to degrade, as well as the relative amount of nitrogen (measured by the C/N ratio, for example) are the main governing variables. Organic matter decomposition releases large quantities of CO_2 to the atmosphere. Under certain conditions significant amounts of trace gases such as methane and nitrogen oxides are also emitted, these playing an important role in the greenhouse effect. It is also the main process that controls the stock of nitrogen in the soil which is one of the main limiting factor for vegetation growth.

Knowledge of the stock of nitrogen in the soil is critical when modelling the canopy functioning, because nitrogen is recognised as one of the main limiting factors as illustrated in figure 2.4.

The energy and water fluxes are essentially determined by the biophysics of the surface, the carbon fluxes are additionally controlled by the biochemistry. The interlinking between these is shown in figure 2.5 below.

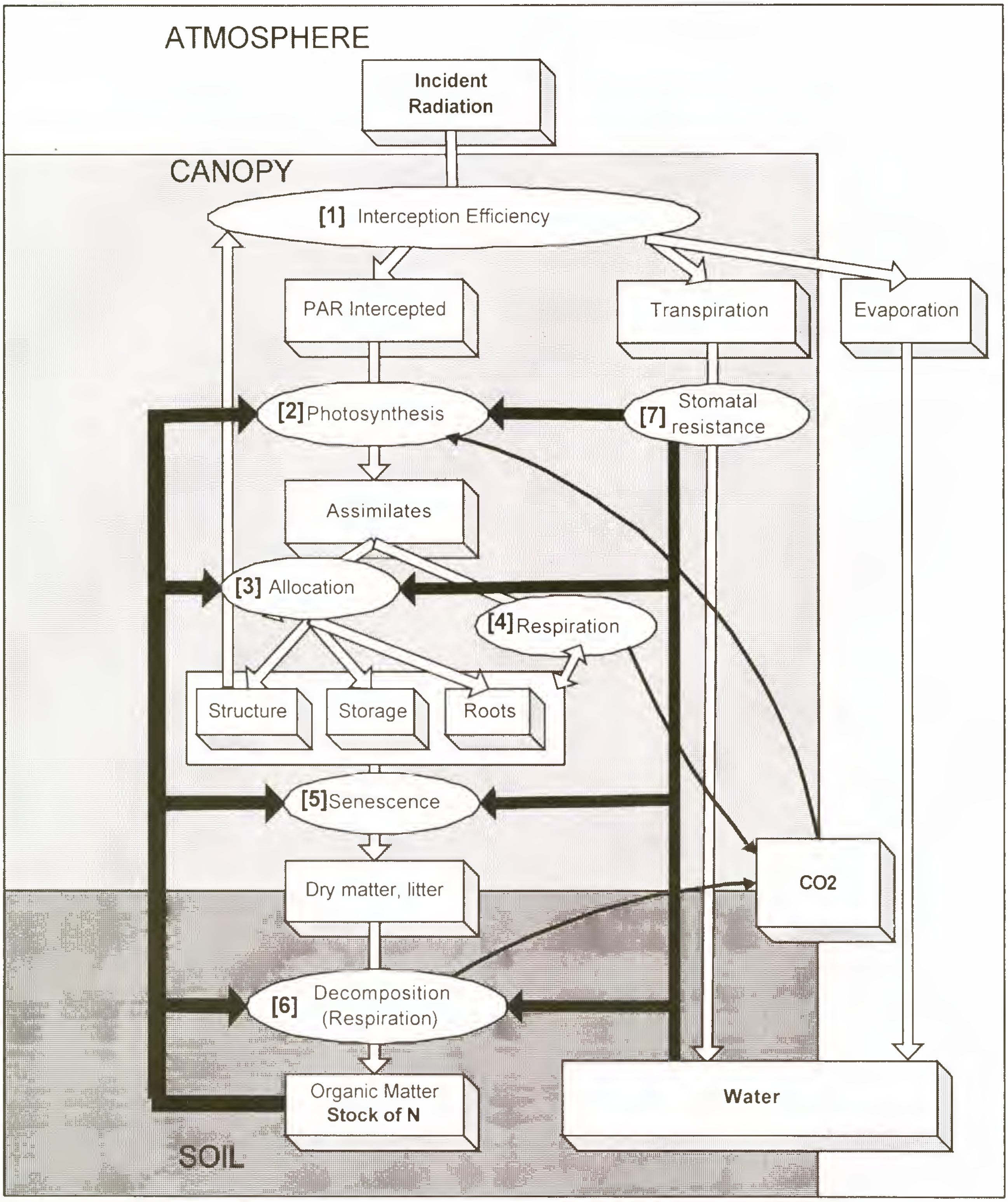

Figure 2.4. *Schematic representation of the basic processes in canopy and soil functioning models (the numbers in the figure refer to the items discussed in the text above).*

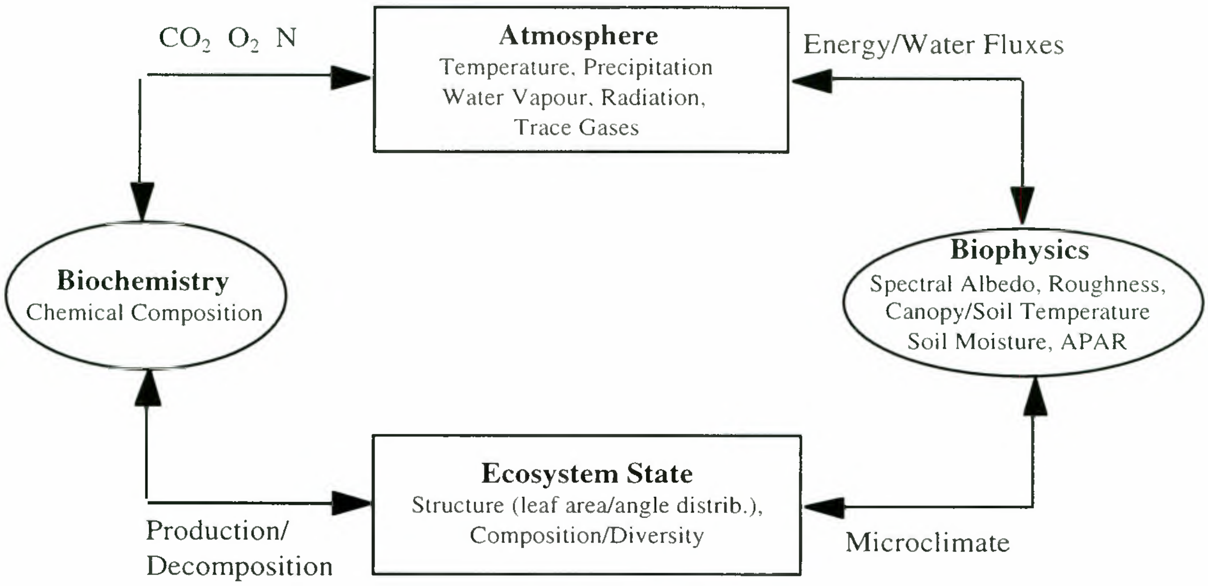

Figure 2.5. *Biospheric interactions and process variables to be retrieved from satellite*

2.3. From Processes to Radiances

2.3.1. Energy and Water

The heat fluxes depend critically on three observables that can be derived from remote sensing data:

a) surface spectrally integrated hemispherical reflectance (albedo), which requires knowledge of the Bi-directional Reflectance Distribution Function (BRDF)
b) 'surface temperature', which must be defined more precisely (see e.g. Norman and Becker (1995) in this context of a satellite mission for land surface studies;
c) spectral emissivity for the calculation of net radiation;

Albedo and Bi-directional Reflectance Distribution Function

From the previous sections, it is clear that the radiation balance at the land-atmosphere interface is of crucial importance for various climatic and environmental processes. In the solar spectral range, the energy available for living and abiotic processes is the difference between the amount of incoming radiation and the amount reflected by the surface.

At any particular wavelength, the beam of light coming directly from the sun is called direct solar radiation, while the radiation originating from all other directions is known as diffuse or sky radiation. Together, these two components constitute the total incoming solar radiation.

Since the apparent size of the sun is small but finite, the direct beam appears strongly collimated. Under clear sky conditions, the bulk of the incoming energy originates from a very limited range of directions, and these change rapidly with time of the day. Diffuse radiation, on the other hand, includes the light scattered towards the surface from all other directions of the upward hemisphere. This radiation distribution is also strongly dependent on angles, because it results from the interaction of the direct beam with the atmosphere (the scattering phase functions of the gas molecules and of the aerosols are highly asymmetric), and from the multiple scattering of light that has been bouncing back and forth between the atmosphere and the surface, which is itself strongly anisotropic. The angular distribution of diffuse radiation also changes appreciably during the day.

The absorption of solar radiation by the surface is not directly measurable, but must be estimated as the residual between the incoming and reflected radiation. However, all natural and man-made surfaces reflect light differently in different directions. This anisotropy results from both the structure and the optical properties of the considered objects. Reflectance measurements for typical surfaces under a variety of illumination and observation geometries show that this angular reflectance distribution exhibits a general bowl shape, with larger reflectance values for high illumination or zenith angles, a noticeable asymmetry between the forward and backward hemispheres, and other features such as specular reflectance peaks. The presence, angular location and strength of these features are of course dependent on the angular distribution of incoming radiation, which is itself strongly anisotropic, as explained above, and on the properties of the surface itself (figure 2.6).

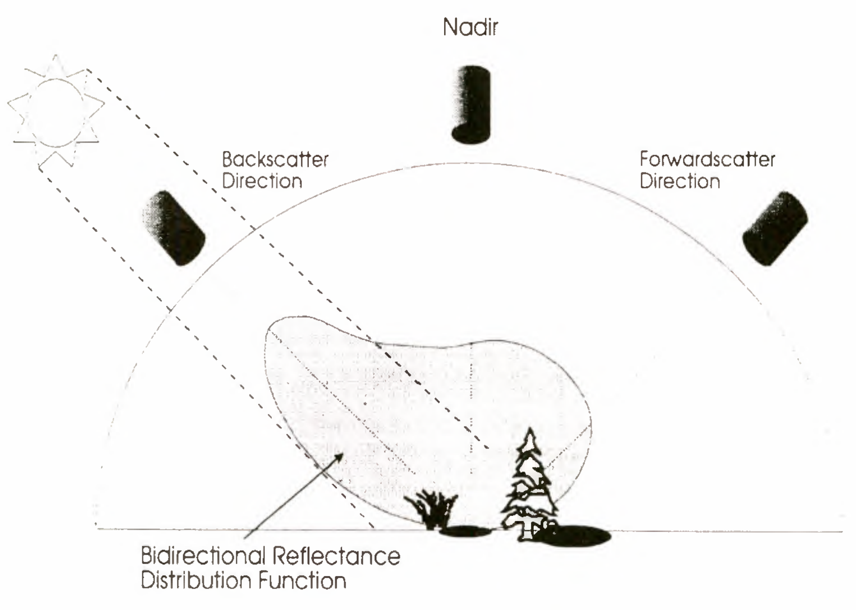

Figure 2.6. *Conceptual diagram illustrating how directional remote sensing is used to evaluate the BRDF (after Irons et al. 1991)*

The critical variable describing the interaction of light with a natural or man-made surface is therefore the bidirectional reflectance distribution function. This is a theoretical concept used to describe the probability that light originating from a single direction will be scattered in any other particular direction (Nicodemus et al., 1977). This distribution function cannot be measured, because all actual sources of light and all real instruments are of finite size. Field measurements correspond to hemispherical conical reflectance measurements.

All imaging space sensors acquire data over large areas by accumulating observations for individual locations with narrow instantaneous field of view instruments. Each of these elementary observations are therefore highly dependent on the particular position of the sun and of the sensor with respect to the observed target, on the composition of the atmosphere and on the structure and properties of the surface at the time of the measurement. No simple strategy of observation in a single direction can provide a satisfactory sampling to untangle these issues because even when the observation angles are restricted to a small range of angles (e.g. with nadir-looking high resolution instruments), the position of the sun keeps changing during the day and throughout the year. The quantitative, reliable and accurate interpretation of remote sensing data therefore requires adequate angular sampling of the directional reflectance field and since the anisotropy of the surface and the atmosphere are both spectrally variable, directional and spectral measurements must be combined.

These difficulties must be resolved by analysing remote sensing data with coupled surface-atmosphere models capable of describing at once the directional and spectral properties of the radiatively coupled media. This situation presents both a challenge and an opportunity. The challenge is to achieve the simultaneous description of the directional and spectral properties of the surface and the atmosphere, in three dimensions and through time, and the inversion of these coupled models against suitable observational data sets. The opportunity is to characterise both media in a coherent and integrated way, and to retrieve information hitherto unaccessible from standard methods, such as the structural properties of the surface.

Significant research efforts over the last decade have resulted in major advances in radiation transfer theory and modelling, both for the atmosphere and the surface media, but a few major issues remain to be addressed, for instance to account for the three-dimensional nature of the problem, especially over terrestrial surfaces. One of the main difficulties encountered in modelling terrestrial surfaces results from its very large heterogeneity at many different length scales. The surface heterogeneity issue enters the radiation transfer problem through the interaction of the radiation with the complex three-dimensional structure of natural media such as soils and vegetation canopies, and in particular through the process of multiple scattering, since the light trapped by the observing instrument has been interacting with various scatterers before exiting in the direction of the sensor. Clearly, the severity of this problem depends on how the natural length scale of variability in the environment compares to the dimension of the instantaneous footprint of the instrument: The smaller this footprint, the more likely the observed target may be radiatively homogeneous, and the easier the task of modelling this target. It is therefore an advantage, both from a directional and from a spectral point of view, to deal with smaller individual targets and high spatial resolution instruments.

Figure 2.7 shows reflectance factors for a coniferous forest, modelled with a 3-dimensional Monte-Carlo radiative transfer code (North, 1996). The top plot shows the BRDF in the red band, displaying a very pronounced hot-spot (see below). The lower plot is for the infra-red, which shows a much less severe variation.

It has been seen above that the physical surface parameters retrievable from optical remote sensing data that would be most useful for climate and environmental purposes relate to the albedo and structure of the surface. In the case of vegetation canopies, the latter refers to the amount, location and orientation of the leaves. The next question, then, is how these parameters can be estimated from a knowledge of the BRDF of the surface.

The spectral albedo of the surface, i.e., its bihemispherical spectral reflectance, is simply obtained by integrating the BRDF over all illumination and observation angles, for the particular atmospheric and illumination conditions at the time of the measurements. It is important to remember, though, that this quantity is highly dependent on the geometry of illumination and on the state of the atmosphere, as well as on the nature and properties of the surface. It is therefore not an intrinsic property of the surface itself. Another quantity that may be useful in some cases is the directional hemispherical reflectance of the surface, which explicitly depends on the direction of the incoming radiation. Both of these concepts and their derivatives must be estimated with the help of bidirectional reflectance models. Because only the shape (i.e., the effect of the anisotropy) needs to be accurately described, parametric models can be used for this purpose.

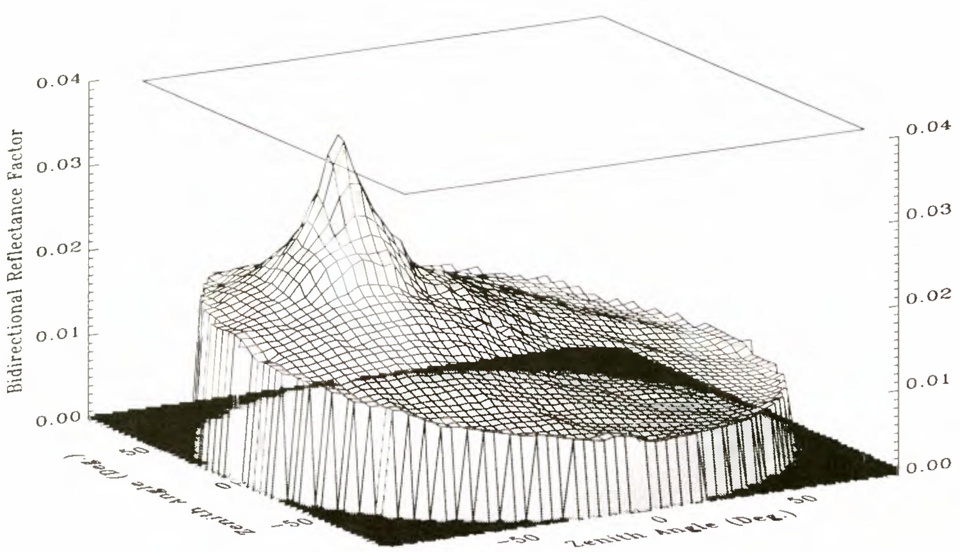

Figure 2.7a. *BRDF of a coniferous forest at 690 nm (from North, 1996)*

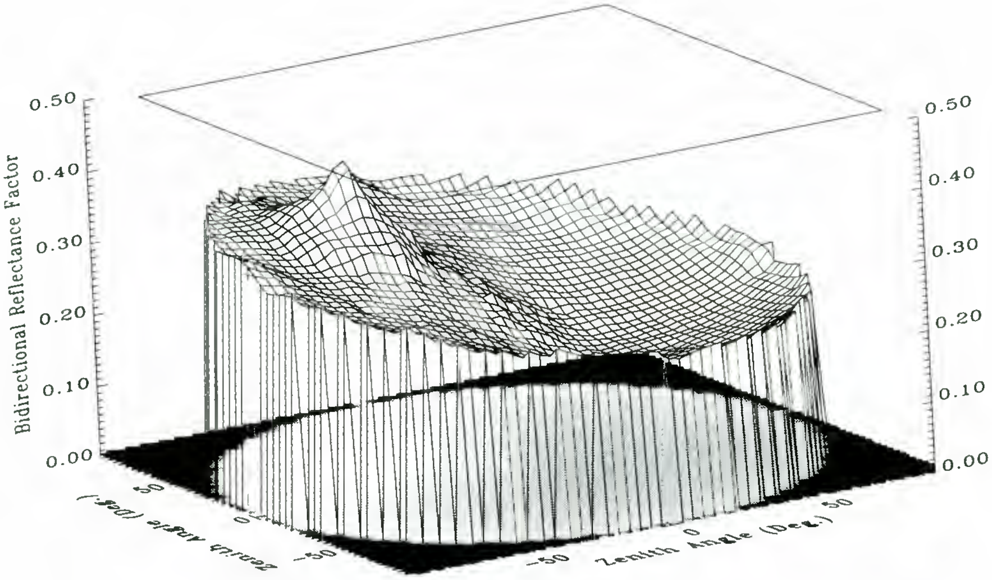

Figure 2.7b. BRDF of a coniferous forest at 870 nm (from North, 1996)

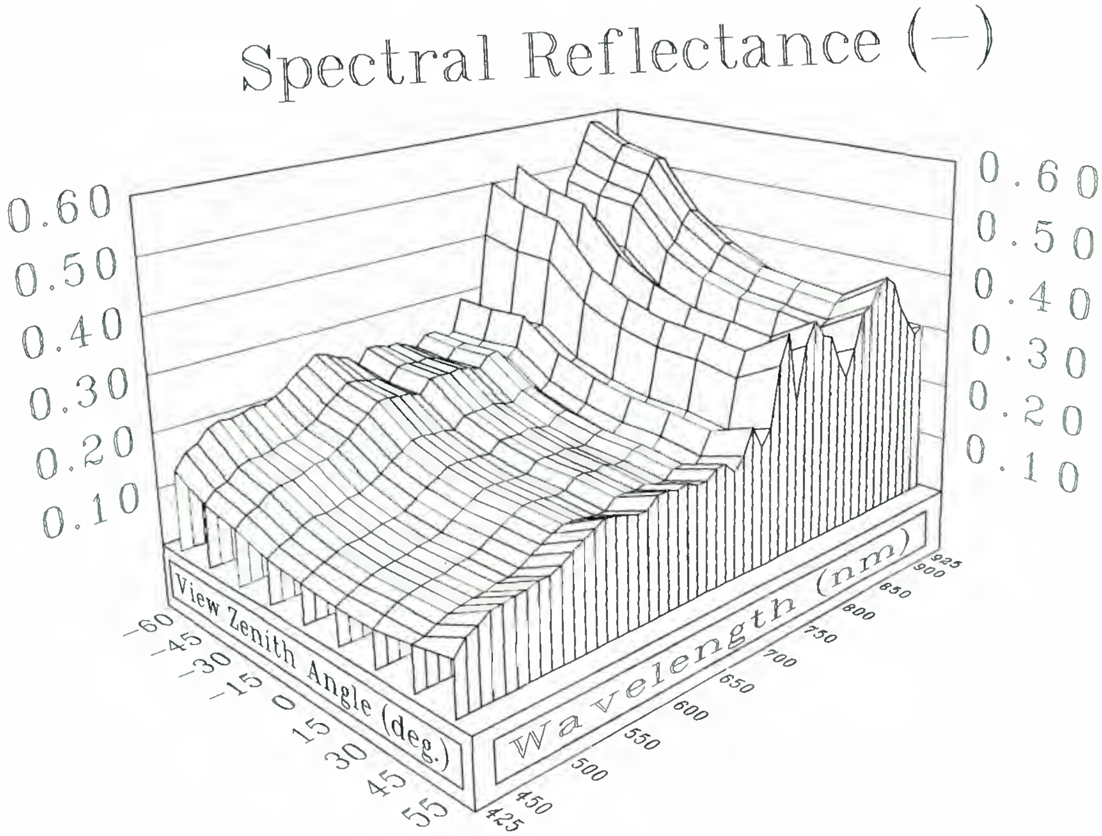

Figure 2.8. Measurements of directional spectral reflectance

An example of actual measurements of directional spectral reflectance done with the Advanced Solid State Array Spectroradiometer (ASAS) over a fallow field in Niger (HAPEX-Sahel) is given in figure 2.8.

The characterisation of the structure of the surface and in particular of vegetation canopies is more difficult to achieve because it relies on the exploitation of the dependency of the anisotropy of the surface on these parameters. Hence, physically-based bidirectional reflectance models must be inverted against multiple measurements obtained simultaneously for the area of interest under a variety of geometries of illumination and observation. Since the position of the sun relative to the target of interest cannot be controlled, the observational strategy focuses on acquiring observations under a variety of view angles.

For this latter purpose, it is clear that the angular observation strategy should pay particular attention to those features of the BRDF which carry information on the structure and properties of the surface, especially the hot spot. This latter feature is an increase in reflectance in the backscattering region (phase angles close to zero), due to the absence of shadows in the scene at those angles. The BRDF varies sharply in this angular region, and the shape of this function can be interpreted in terms of the structure of the canopy or soil being observed. The further away from these ideal observing conditions, the more measurements are needed to retrieve this kind of information from the data.

A sufficient sampling of the BRDF can also serve to document the orientation distribution of the scatterers (leaves in the case of a plant canopy). Other environmental parameters, such as the Leaf Area Index (LAI) of a vegetated area can sometimes be estimated from spectro-directional data. In all cases, however, the accurate estimation of these surface properties heavily relies on the availability of high quality data, as well as of appropriate models for the interpretation of these data by inversion. Preliminary results have recently been obtained through the inversion of one-dimensional coupled surface-atmosphere models against AVHRR data, and this research field is currently very active. The main limiting factor to further progress at this time, however, is the lack of reliable, accurate directional and spectral data at the appropriate scales and resolutions. A space mission acquiring both directional and spectral data will therefore constitute the most significant event to stimulate and establish a better understanding of the structure and properties of our natural environment.

An early contribution to the directional observation requirements will be the experience gained from the POLDER instrument, which will be launched on the Japanese ADEOS satellite in 1996.

Surface Temperature

For very simple systems, e.g. a slab of some homogeneous material in contact with still air, heat transfer can be described by equations relying on a clear and precise theoretical foundation. When applied to heterogeneous land surfaces such equations define effective state variables and parameters, effective meaning here that the sensible heat flux calculated using spatially averaged (in a yet to be specified manner) surface temperature and heat transfer coefficients, has the same value as the one which would be obtained by calculating the area integral of the actual spatial distribution of sensible heat flux.

In the literature many examples can be found of applications of equations conceptually similar to the ones applying to truly homogeneous surfaces, but involving several semi-empirical corrections to account for a fundamental characteristic of partial canopies: the complicated distribution, over the specific area of the object, of temperature and, therefore, of heat sources and sinks. As a first approximation one should consider two different temperatures for canopy, T_c, and soil, T_s. The use of a one-dimensional equation to describe heat transfer from a single source implies the existence of an appropriate, 'effective', aerodynamic temperature, T_{0a}, as well as of an additional heat resistance to heat transfer (see e.g. Norman et al., 1995). Experience so far, however, indicates that this approach leads to empirical correction factors difficult to use in any general manner.

A more promising approach for both modelling and observation of heat transfer from partial canopies is the explicit consideration of the thermal heterogeneity; this has, however, an immediate consequence for the application of thermal infrared radiometry in this context. In such cases the observable directional radiometric temperature depends on the view angle (Norman et al., 1995), i.e. on the fraction of the field of view, f(θ), occupied by the canopy at a given view angle θ. The same authors proposed a parameterisation of sensible heat flux for partial canopies based explicitly on the determination of T_c and T_s.. The advantage of this formulation is that it avoids empirical adjustments by using estimations of T_c and T_s which can be obtained from measurements of directional radiometric temperature at different view angles (Kimes, 1983).

Directional measurements in the thermal infrared might therefore allow for the replacement of semi-empirical corrections with a more robust concept relying on observations of the thermal heterogeneity of surface elements such as partial canopies. For large homogeneous targets, such as the large oasis and the desert of the Hei He basin in the Gobi desert (Fig. 2.9) this effect is very significant. Over the irrigated lands the nadir view gives temperatures up to 10 K higher than the forward look even with the low resolution ATSR observations. In most cases vegetation patches are heterogeneous at large length scales, so that higher resolution measurements are required to observe and exploit the directionality of observations to determine both canopy and soil temperature.

Accordingly, thermal infrared measurements should be done at two or three view angles chosen out of the larger ones selected for the BRDF observations.

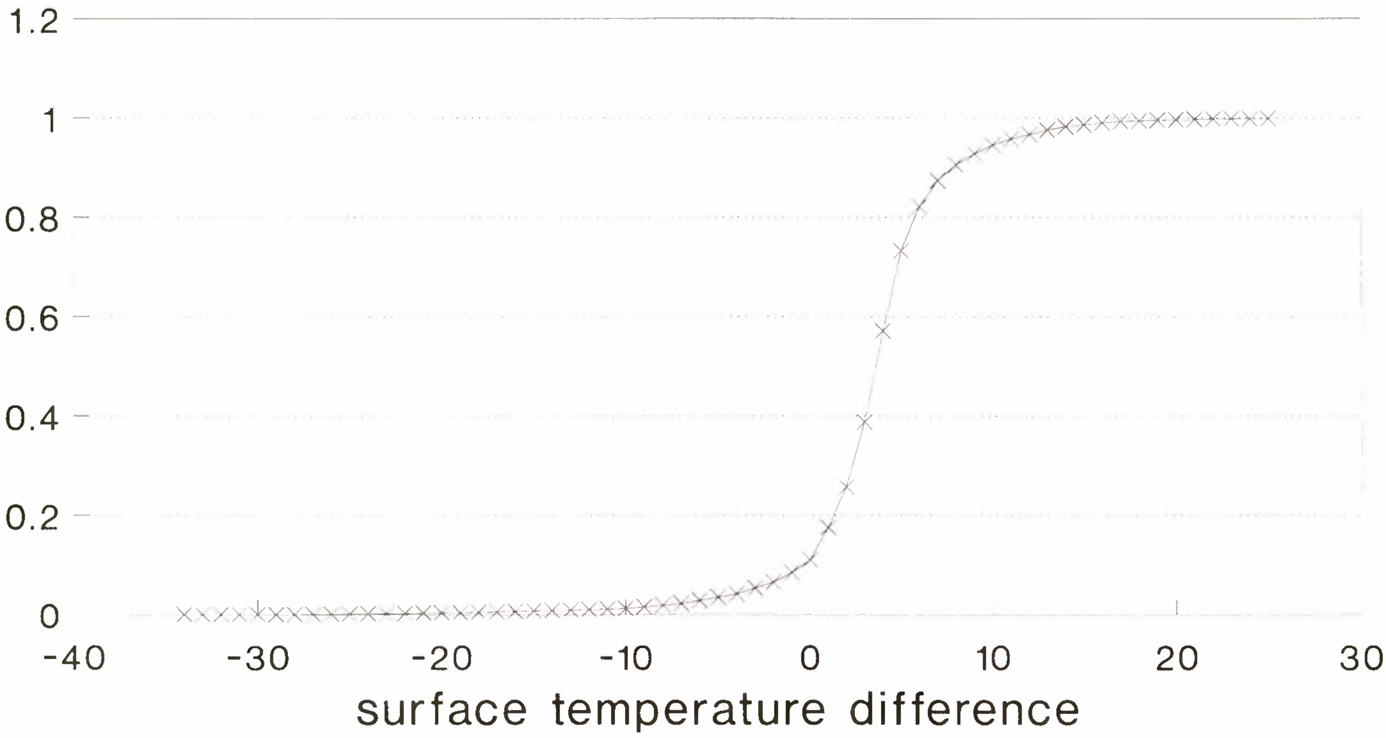

Figure 2.9. *Cumulative frequency distribution of the surface temperature differences between nadir and forward look as observed by ATSR at 12 μm wavelength*

Spectral Emissivity

Upwelling longwave radiation flux is an important term of the land surface energy balance; the shortwave and longwave balance of radiation flux density determines the energy available at the land surface, which is the main driver of land surface hydrology and of interactions of the land surface with the atmospheric boundary layer.

As regards the longwave flux, the net flux, i.e. downwelling minus upwelling flux density, is required with an absolute accuracy of 20 Wm^{-2}: to achieve this accuracy both upwelling and downwelling radiation flux density must be known with an accuracy better than 10 Wm^{-2}.

The at-surface upwelling longwave radiation flux density, L_u, can be either measured with broad band radiometers or calculated (spectral integration) from surface temperature and spectral emissivity; knowledge of the latter is particularly important in those spectral regions where $\varepsilon < 1$.

When ε is known in those regions where it is close to 1 only, the same emissivity would have to be applied to the entire spectral range of integration necessary to estimate L_u. This gives errors easily in excess of the 20 Wm^{-2} requirement, as shown by the data in table 2.2, where the spectral emissivity data of Kahle and Alley (1992) and of Schmugge et al. (1995) for the region 8 to 12 μ and of Zhengming and Dozier (1989) for the region 3 to 13 μ where used.

	Black-body	Kahle $\varepsilon(\lambda)$	Kahle $\varepsilon(11.5\mu)$	Schmugge $\varepsilon(\lambda)$	Schmugge $\varepsilon(11.5\mu)$	Zhengming & Dozier $\varepsilon(\lambda)$	Zhengming & Dozier $\varepsilon(11.5\mu)$
$L_u(Wm^{-2})$	459.27	435.34	454.0	430.80	454.0	397.5	454.
ε^*	1.	.948	.988	.938	.988	.865	.988

Table 2.2. *Estimated upwelling longwave radiance flux density using $\varepsilon(\lambda)$ respectively $\varepsilon(11.5\mu)$, ε^* is the effective emissivity calculated from the ratio between L_u and the blackbody radiation flux density at the same temperature*

2.3.2. Ecosystems characteristics and biochemistry

The previous review (2.2.3) of the main processes that govern canopy and soil functioning highlights the very specific and critical role played by canopy structure and biochemistry. They control directly several elementary processes and reveal indirectly the botanical composition, physiological status of plants and the functioning of the soil. Many biophysical and biochemical variables potentially provide pertinent information on the system:

- Canopy structure

Canopy structure governs light interception, rain interception and canopy roughness. It is certainly the main variable, that drives canopy functioning on short time scales. It is also the main indicator of species composition, phenological stage and physiological status of the vegetation.

- Canopy biochemistry is characterised by:

  - Leaf chlorophyll content, governs the photosynthetic capacity of the canopy.
  - Specific leaf weight, the dry mass of a unit leaf area, controls the building of the leaf area from the mass of assimilates allocated to the leaves. For leaves, it is also very strongly correlated to the carbon content.
  - Heat of combustion, corresponds to the amount of the energy stored as chemical bonds in one unit mass of vegetation organs. It is therefore one of the main drivers of the photosynthetic efficiency when expressed in mass dry material produced per unit of intercepted photosynthetically active radiation.
  - Protein or nitrogen concentration drive the main physiological processes such as photosynthesis and allocation of assimilates. It also controls the rate of decomposition

of the organic matter, while lignin, cellulose and hemicellulose concentrations are playing a secondary role. Protein and nitrogen concentration are very strongly correlated.

The spectral variation in the optical domain (Figure 2.10) is mostly governed by the absorption characteristics of vegetation elements and soil.

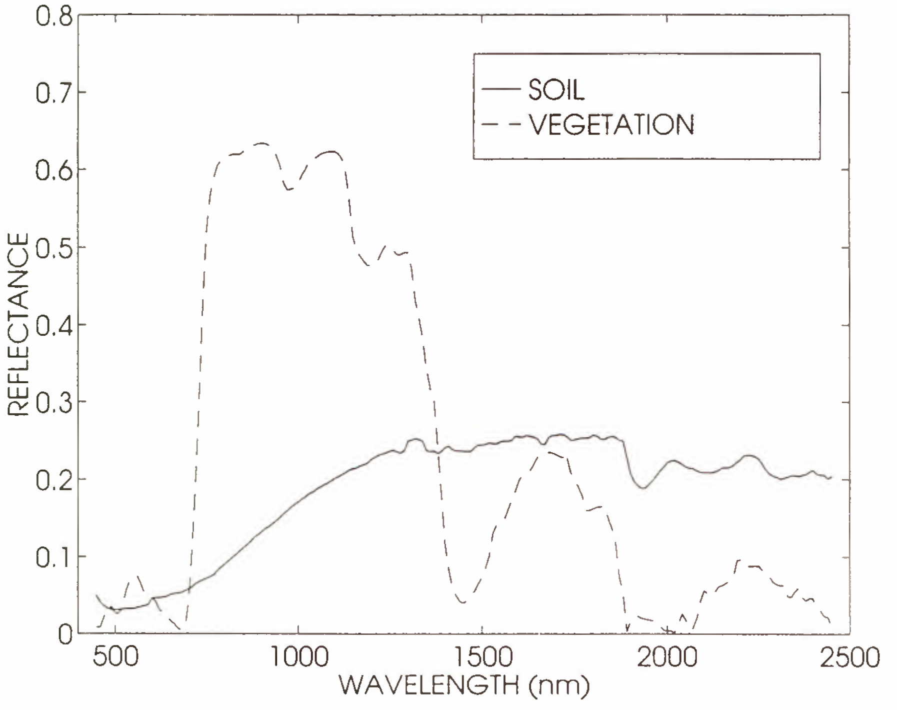

Figure 2.10. *Typical reflectance spectra of vegetation and soil*

For the vegetation the three main compounds are:

- chlorophyll, which absorbs in the visible domain (below 800 nm)
- Plant -water, which absorbs mostly in the near to middle infrared spectral range
- biochemicals such as protein, lignin, cellulose, hemicellulose that constitute most of the leaf dry mass absorb in the near and middle infrared domain.

The absorption signal associated to the detailed biochemical composition is not very strong, and variations occur between different species. Recent advances show that robust and reliable relationships can be developed to estimate chlorophyll and water content and leaf specific weight (Fourty et al., 1996; Baret and Fourty, 1996). In more restricted conditions, experimental work, mostly performed with the AVIRIS sensor, shows that more detailed biochemical composition could be estimated using a high spectral resolution data in the 1000-2500 nm range (Johnson and Peterson, 1991; Smith and Curran, 1992; Wessman, 1992; Gastellu-Etchegorry et al., 1994; Martin and Aber, 1994). The compounds that can be reliably estimated are the specific leaf weight, chlorophyll and water contents. This leads to the variables that should be observed:

– *Canopy structure*

Main canopy structure characteristics that could be retrieved from BRDF and spectral data are Leaf Area Index (LAI), Leaf Angle Distribution (LAD), size of the leaf relative to canopy height, and clumpiness. Canopy structure could be retrieved by inversion of dedicated physical models.

– *Light interception efficiency*

Light interception efficiency by photosynthetically active elements is fully described by the illumination geometry (sun position, diffuse fraction) and canopy structure. Depending on the time scale of vegetation functioning models used, light interception efficiency should either be computed throughout the day or integrated over the day. Although semi-empirical relationships were proposed to estimate the daily integrated value of light interception, accurate estimates of diurnal variation of this quantity necessitate knowledge of canopy structure that can be derived from spectral and directional variations of reflectance.

– *Chlorophyll content*

Studies related to the estimation of chlorophyll content generally involve measurements around the red edge located in the 600 - 800 nm spectral region. The 'red edge' corresponds to the sharp variation of chlorophyll absorption, between maximum absorption in the red and zero absorption in the near infrared. Determination of chlorophyll content is quite important because under some limiting factors, it is strongly correlated to nitrogen content. Thus, it is an indirect way to estimate nitrogen content.

– *Water content*

Several studies attempted to estimate leaf water content (Danson et al., 1992; Gao and Goetz, 1992; Jacquemoud et al., 1995) from canopy spectral reflectance. Results show that leaf or canopy water content can be estimated by remote sensing techniques. This may provide new avenues to describe the water content of leaves that complements the information provided by microwave sensors that are more sensitive to the integrated water amount in the canopy and in the soil, depending on the particular configuration (frequency, polarisation, incidence angle) used. Acquiring reliable information on the water content of plants and soils would provide significant constraints on the soil-vegetation models used to describe the state and evolution of the surface.

– *Specific leaf weight*

Very few studies have been focussing on the determination this variable using space data. However, results both at leaf and top of canopy level show that reasonable estimates of the leaf specific weight are derived from the spectral variation of the reflectance.

2.4. The Need for a Spaceborne Mission

Large data sets acquired on a selection of representative biomes are needed at small length scales to calibrate and assess coupled surface-atmosphere models. Variables that cannot be directly retrieved from a quantitative analysis of remote sensing data must be estimated from appropriate models, which are themselves constrained by data from remote sensing and other sources.

It has been shown in experiments such as FIFE that surface radiometers alone are insufficient for describing the surface radiation budget of a region to the required accuracy (Field et al, 1992). Airborne instruments can be very useful for local studies, but the cost of operating these aircraft in remote, but scientifically important locations, together with the logistical difficulties of such operations, can considerably increase the costs of using airborne instruments.

Satellite instruments have the advantages of consistency and stability and have the ability to take data of many different areas in a short time. Some of the variables listed in 2.2.2 are obtained using algorithms and models which require synchronous or nearly simultaneous data acquisitions over the same region.

The use of a satellite instrument for inferring components of the surface energy budget is cost-effective. There are no other potential ways of making these observations at any, and every point of the globe. The necessary information for improving the parameterisations of the large scale models can be derived from observations made on key sites. These observations from a satellite mission can be used to validate global models, which may then be used to derive estimates of the components of the surface radiation budget elsewhere. The use of these observations for validating models is an approach which will allow us to take advantage of all the relevant observations, which may be assimilated into the global models or used to validate them.

A space-borne Land-Surface Processes and Interactions Mission is therefore needed to help develop, initialise, calibrate and validate land surface process models. It needs to provide as much reliable and accurate information as possible on the fundamental processes and mechanisms that control the state and evolution of the land surfaces and their interactions with the climate system. It needs to provide data relevant to the study and understanding of biogeochemical cycles and the energy and water cycle. While we can impose certain criteria that the mission must meet, in terms of sampling, it should retain a high degree of flexibility, since it must serve the various needs of a diverse scientific community.

2.5. International Initiatives

There are several large umbrella organisations such as the WCRP (World Climate Research Program) and IGBP (International Geosphere Biosphere Program) who have initiated programs to investigate the interactions of the land surface with other components of the biosphere. These fora, as well as numerous national institutions, have defined a number of research priorities and continue to provide the necessary motivation and scientific authority to justify such a mission IGBP (1992). IGBP was launched by the International Council of Scientific Unions (ICSU)in 1986 with the objective of 'describing and understanding the interactive physical, chemical and biological processes that regulate the Earth system' (CEOS, 1992). IGBP is implemented through Core Projects and Tasks. There are at present five established core projects. These are:

BAHC (Biospheric Aspects Hydrological Cycle),
LOICZ (Land-Ocean Interactions in the Coastal Zone),
IGAC (International Global Atmospheric Chemistry),
GAIM (Global Analysis Interpretation Modelling),
GCTE (Global Change Terrestrial Ecosystems).

In this context the WCRP has initiated the Global Energy and Water Cycle EXperiment (GEWEX). The overall goal of GEWEX is to determine the fluxes of water and energy globally, including land surfaces and their interaction with the atmosphere. Here (as opposed to WCOS) the emphasis is on new satellites sensors systems. The more recent report by JSC (1994) specifies additional WCRP satellite data requirements such as multispectral albedo and land surface temperature. The core projects Biospheric Aspects of the Hydrological Cycle (BAHC), Global Change and Terrestrial Ecosystems (GCTE) and Land Use and Cover Change (LUCC) are relevant elements of the context of our investigation. IGBP/BAHC studies vegetation-water interaction on regional scales. This involves modelling of water and energy balance, scaling algorithms, measurements of vegetation-water interaction and surface fluxes. To this end simultaneous satellite measurements are being conducted over several sites in Europe, North Africa, USA, Russia and China. Frequent coverage of the area by high resolution images are the highest priority requirements for this project. Measurements by high resolution sensors would be very valuable in the future.

IGBP/GCTE is concerned with ecosystem studies and modelling at all ecosystem scales. It has adopted a transect approach for studying global change impacts on biogeochemical cycles and for developing ecosystem dynamics models. The transects (about 1000 km × 200 km) consist of a series of research sites along an underlying environmental gradient, such as temperature or precipitation. Examples include the eastern Siberian transect, and others are being designed so that the sites of older experiments can be revisited in future, providing the basis of a longer time series of observations. High resolution remotely sensed data will be critical in detecting change in both ecosystem composition and function along the transects, in interpolating within the transect between the sites of intensive study, and will provide valuable data for model development.

IGBP/LUCC aims not only to map land use and land cover but also to understand how and why change occurs in response to environmental and anthropogenic drivers. The ultimate objective of the project is to develop models able to predict these changes. The use of high spatial resolution is considered mandatory, although aimed at specific sites and temporal frequency; improved spectral and resolution and radiometric accuracy will be an asset, especially detailed spectra to detect specific components of vegetation, soil and rocks.

There are many other national programmes whose aims include contributing to these projects. To support these programmes several agencies are developing global scale instruments, including Europe's MSG, MERIS, AATSR, VEGETATION and ASAR; NASA's MODIS, SeaWiFS and MISR, and the Japanese ASTER, but none of these are addressing the small length scale.

Table 2.3 sets out a list of geophysical parameters that could be retrieved from a land-surface processes and interactions mission, and the priority with which different IGBP projects need them.

Parameters\IGBP programme	BAHC	IGAC	LOICZ	GCTE	LUCC	JGOFS
Cloud top temperature	2	2	0	3	0	0
TOA radiation	1	2	0	0	0	1
Cloud top albedos	0	1	0	0	0	0
Aerosol total content	0	1	0	0	0	0
Land surface albedo	1	3	2	1	1	0
fractional PAR	1	1	3	1	2	0
Vegetation state	1	1	1	1	1	0
Land cover type	1	1	1	1	1	0
Land surface temperature	1	1	3	1	1	0
Snow cover	1	3	3	1	0	0

Table 2.3. *IGBP satellite data requirements and priorities relevant for a Land Surface Processes Mission (IGBP/DIS, 1995)*
Key: 0 = irrelevant, 1 = high, 2 = medium, 3 = low priority

Therefore, in addition to these activities, high resolution data will be important to characterise and monitor a network of 50 - 100 intensive sites for monitoring change and developing global vegetation models. These sites will also serve the Global Terrestrial Observing System (GTOS). The selection of the optimum set of sites is under development by a GTOS Task Force. They will require the highest resolution data available on both vegetation structure and function. The sites will have many ground-based measurements and process studies for algorithm development and validation of new remote sensing instruments.

3. Research Objectives

The principal objective of this mission is to acquire the accurate and reliable quantitative measurements needed to improve our understanding of the nature and evolution of biosphere-atmosphere interactions, and to contribute significantly to a solution of the scaling problems for energy, water and carbon fluxes at the Earth's surface. The measurements are to be made on space and time scales consistent with large-scale international field experiments, namely several 10-1000 square kilometres, and throughout several seasons.

The Earth Explorer Surface Processes and Interactions Mission will achieve this objective by implementing a strategy of data acquisition from an advanced high resolution spectro-directional space sensor, and by supporting the development of the tools and techniques of data interpretation to:

- increase the understanding of biophysical processes and land/atmosphere interactions at the local scale (small length scales)
- exploiting the increase in knowledge of (small scale) processes and to advance the understanding of these interactions on a global scale by extrapolating through time and space using process models.

The role of the surface in the partitioning of the energy balance, i.e., the spatial and temporal distributions of the sensible and latent heat fluxes to the atmosphere, the radiative budget at the surface, and the heat flux into and out of the soil must be studied. Of these, only some components of the radiative fluxes are observable from space, namely the amounts of solar energy reflected and of thermal energy emitted by the surface-atmosphere system. All other components of the energy balance must be estimated through integrated models, which also require an accurate description of the nature of the surface. Hence, we absolutely need reliable observations of the radiative fluxes to constrain these models and to establish the properties of the surface.

The particular role of the vegetation in the control of the energy, water and carbon cycles at the surface needs to be carefully investigated. These controls largely take place as a result of the process of photosynthesis, which exploits solar energy at wavelengths shorter than 700 nm to synthesize organic carbon compounds from atmospheric carbon dioxide and nutrients. Water vapour extracted from the soil is released through evapotranspiration in this process. Since chlorophyll exhibits very strong absorption bands in the range 400-700 nm, we need a good spectral resolution within that range to exploit differential absorption features to derive estimations of the quantity of chlorophyll.

Both the surface energy balance and the physiology of plants are dependent on the temperature of the environment. It is therefore essential to have access to this crucial parameter, which also represents the thermodynamic state of the system. This parameter changes rapidly in space and time, and it is realised that its observation should occur ideally at a time which is optimal for observation of reflected solar radiance (late morning). This may not be optimal for the evaluation of the thermal state of the system, but it is believed nevertheless, that such information is sufficiently essential that it can be adapted to the models to take advantage of this information.

An instrument designed for the primary mission described above will also be useful for a number of investigations that require similar observational capabilities. An example of such a secondary application would be agricultural monitoring at selected sites, to improve our ability to detect significant changes in the growth and development of crops, and to provide relatively high resolution data to operational programmes such as the MARS project of the European Commission, in support of the Common Agricultural Policy. Because of the greater discrimination of vegetation and cover types that will be possible with an instrument with high spectral resolution and directional capabilities, another important secondary application will be the detection of land cover and land use changes.

Thus, to meet the research objectives of a Surface Processes and Interactions Earth Explorer Mission addressing the scientific requirements outlined in the previous section the following is needed:

- An imaging mission exploiting the optical range of the electromagnetic spectrum from the Visible into the Thermal Infrared
- Selective intermediate to high resolution observations of local and regional areas with full global access
- Repetitive target observations on a continuous basis i.e. observations at any time of the year

As will be seen below, it is proposed to meet these objectives by designing, implementing and operating a high spatial and spectral resolution imaging sensor, capable of repetitively acquiring data for any particular site under a variety of observation angles.

4. Observation Requirements

4.1. Introduction

Since all terrestrial surfaces are always observed through the atmosphere, which also exhibits significant absorption and scattering, and since the surface and the atmosphere are in fact intimately linked from a radiative point of view through multiple scattering, the proper interpretation of satellite remote sensing data requires the solution of the problem of radiation transfer in the coupled surface-atmosphere system. This issue can only be addressed meaningfully through the analysis of the spectral properties and the anisotropy of the joint system, i.e., through its observation simultaneously under a variety of illumination and view angles over the adequate spectral range. The desired instrument must therefore be able to acquire spectral data under multiple views for each target of interest within at most a few minutes. Such a capability will, however, also be useful to characterise the structure of the surface in ways not accessible through the spectral measurements alone.

As a high spatial resolution instrument will have a relatively small swath on the ground, and as the geographical location of the targets of interest beyond the year 2000 cannot be specified at this early stage, it is highly desirable that such an instrument be capable of visiting any and all locations on the globe, with a frequency permitting at least the documentation of seasonal changes.

4.2. Sampling Requirements

4.2.1. Geometric Requirements

Spatial Resolution

The natural environment is extremely variable on a wide range of spatial and temporal scales. However, to the extent that the focus of this mission is on biosphere-atmosphere interactions and the effect of various possible anthropogenic changes, human scales are those of most interest in this context. Since the typical size of plants is of the order of one to a few meters (horizontally), it would be desirable to have an instrument that integrates over a few meters. On the other hand, agricultural fields and many other landscape features occur at scales of one to a few hundred metres. A useful compromise is therefore an instrument with a spatial resolution of about 50 m at nadir. This corresponds to the largest areas that can be extensively surveyed on the ground by field researchers, it is the scale of small to medium agricultural plots in many countries, including in Europe, and they also constitute areas for which the slope and aspect can be determined with reasonable accuracy. Further, at this scale the environment is far more likely to behave radiatively as a homogeneous turbid medium than at 250 m or 1 km.

An instrument with this resolution would complement the panoply of existing and future sensors; most of the global instruments currently available for environmental research have a spatial resolution of about 1 km at nadir. The next generation of instruments, to be launched between 1997 and 2002, will capitalize on this heritage but will also provide data at about 250 m resolution (e.g., MERIS, MODIS, MISR). In parallel, a series of existing and future high resolution instruments of the type Landsat and SPOT will continue to provide data at 30 m resolution or less at nadir, but in a few spectral bands only. It is therefore logical to consider a sensor generating data at typically 50 m at nadir, with the directional sampling capability discussed earlier.

Swath Width

A priority of the mission is to supply data across a wide wavelength spectrum at high spatial resolution in support of ground based studies. The scale of these experiments is, as seen from Table 2.1, usually of the order 10 to 100 km. The grid scale of the transects proposed by GCTE are themselves no wider than 100 km. The mission will therefore need to collect data over a swath of the order of 50 kilometres. However, this assumes that the scene being acquired can be centred on the site of interest. Since we need global access in order to view all possible experimental sites, the instrument must be pointable across-track. This is also necessitated by the need for frequent re-visits to any site of interest.

Each target will be accessed frequently in time and each image must obviously overlap to the greatest possible extent with the previous data acquisition. The instrument should achieve a total Earth access within 3 days. The accessability would then increase with increasing latitude.

4.2.2. Directional Requirements

The reason for taking directional measurements is to sample the surface BRDF, and so provide reliable estimates of surface reflectance and albedo, and information on the geometry of vegetation canopies, as well as possibilities to correct for atmospheric effects. The hot spot itself contains information on canopy structure from which light interception under different illumination conditions can be estimated, but the hot-spot can not be effectively sampled for all latitudes of an orbit and at any season. If it were technically possible to systematically acquire data in the principal plane and in particular to adequately sample the reflectance field near the backscattering direction, 5 to 7 measurements would be sufficient to characterise the anisotropy of the surface. However, natural variations in surface conditions and illumination geometries, combined with the constraints of the orbit make it difficult to realise such an ideal strategy.

The limitations associated with observations acquired in a plane other than the principal plane can be partially compensated by acquiring additional measurements over a wider range of viewing angles. Hence, it is estimated that observations from 10 to 15 different angles would provide the desired information with sufficient accuracy.

Directional measurements are useful not only to provide an accurate characterisation of the BRDF of the surface and therefore a reliable estimate of the albedo, they also provide specific information on the structure of the canopy and soil. Such information is not accessible by any other means. However, the only way to retrieve this information is to invert physically-based models against such directional measurements, and the accuracy of the results depends strongly on the number and distribution of the sampling angles. Given the strength of the radiative coupling between the atmosphere and the surface, and the relatively fast rates of changes in weather and illumination conditions, these angular measurements must be acquired in as short a time period as possible, typically within a few minutes, hence within the same orbital pass. When that cannot be achieved, then data acquisitions over consecutive passes may be combined. This solution turns out to be advantageous in terms of illumination angles, since the sun may now be in a different position relative to the target, but it is a major drawback if the atmosphere has changed also. This technique is therefore applicable only to those locations and times where the atmosphere is very stable over the entire period of data acquisition.

Ideally it would be desirable to sample the BRDF not only with different viewing angles but with different illumination angles. However, from a sun synchronous orbit, the time of acquisition (within seasonal variations) is quite constant. The equator nodal crossing time of 11:00 am would allow good illumination conditions but without the impediment of cloud build up which would hamper the mission in the afternoon.

The requirement, which is more critical than the number of observations is the angular distribution of those samples. A nadir view is required because it gives the highest spatial resolution (with a fixed optical system) and the least topographical distortion. Although the geometrical depth of the atmosphere is minimised in this case, this observation angle does not necessarily minimise the atmospheric effects, because the latter depends also on the position of the sun and the aerosol scattering phase function, which is highly asymmetric. The proper characterisation of the aerosol properties and of their effects on the retrieval of surface variables requires observations under very different optical depths, 2 and 3 giving observational angles of 60 and 70 degrees respectively. Acquiring observations at these angles in the forward and backward directions significantly enhances our ability to generate surface products decontaminated from atmospheric effects. Finally, acquisition of views at an intermediate angle of about 30 or 45 degrees will allow us to study anisotropic effects away from the hot spot.

Such a collection of seven views of the same target under nearly identical atmospheric conditions (i.e. using along-track pointing) is considered an adequate minimum to document the effect of the atmosphere and to ascertain surface properties with acceptable accuracy, if these observations are obtained in or close to the principal plane. When these views are closer to the cross plane, a greater number of observations must be accumulated, from a number of different overpasses, to provide a similar amount of information. These must be obtained close together in time, which reinforces the need for across track pointing.

The directional requirements for BRDF measurements are fully consistent with the directional requirements for the determination of both canopy and soil temperature. The TIR measurements are particularly required at nadir and at the largest off-nadir angles selected for BRDF measurements.

4.2.3. Spectral Requirements

Spectral Range

- Visible to shortwave infrared

  This mission is intended to facilitate the study of a wide variety of surface processes, and different science areas have interest in different spectral ranges. Energy budget studies need information at visible and near infrared ranges, and over the thermal infrared, while plant chemistry studies need narrow bands in the short wave infrared. From recent advances in the analysis of the information content provided by high spectral resolution sensors, it appears that 30 to 40 bands should be enough to describe accurately most canopy or soil reflectance spectra. The precise number of spectral bands required, and their optimal location, are not yet specified; the optimum choice would depend on the type of area and object studied and on the approaches used. For an Explorer instrument it would be highly risky to prescribe these entities too precisely in advance. Thus a high degree of flexibility in the choice of bands should be preserved. No single application will require all of the bands across the large spectral range, however the bands required will be different for each application and surface type. Together the individual applications span the entire optical range with their requirements for observational spectral coverage.

- Thermal infrared

  As stated earlier the prime motivation for the TIR bands is to enable the accurate recovery of the spatial and angular variability of LST. ESA has commissioned a study aimed at defining the spectral requirements for LST. The results of this study have identified that two long wavelength channels in the TIR between 10-12 μm region are required when used in conjunction with a modified quadratic split window algorithm. In addition, the preliminary algorithm will utilise VNIR information to assist in the estimate of surface emissivity information. The algorithm and spectral analysis has shown that generally the rms error in LST recovery is in the region of +/-0.8 K. The study has shown, by simulation, that the bandwidth in the TIR region is not critical and that 1.0 μm wide bands are sufficient. In addition to the above it has been shown in

Chapter 2 that inaccurate knowledge of the spectral emissivity has such a significant impact on the accuracy of the upwelling longwave irradiance to impair satisfactory determination of the net radiation flux density. Data in literature (see Table 2.2) indicate that dips in spectral emissivity in the windows 8 to 10 μm are of particular importance. The instruments should therefore provide observations of spectral emissivity in this spectral window.

Spectral Resolution

Because of the relatively smooth character of absorption features of most biochemical compounds, the spectral resolution is not critical for this application area. Away from the red edge, characterised by a sharp variation of reflectance, a spectral resolution around 15 nm would be sufficient to be able to extract most absorption features from the vegetation. A spectral resolution of about 10 nm will allow a good characterisation of this red edge itself, and these narrower bands would make the instrument useful for a number of complementary applications such as soil science, geology, petrography and mineralogy. For atmospheric correction, 10 nm wide bands should be appropriate (ESA SP-1184). Thus a requirement of 10 nm across the visible to shortwave infra-red spectral range will ensure that the basic building blocks are available. In the thermal infrared a spectral resolution of 1 μm is adequate.

4.2.4. Radiometric Requirements

The quantitative interpretation of remote sensing data can only take place if the data are accurately calibrated and validated. This is especially the case for the numerical estimation of the values of the physical state variables. Some differential techniques, especially those exploiting the differences between measurements in different spectral bands, may appear not demanding in terms of calibration, but it is important to recognize that this is made at the cost of an important hypothesis, namely that the instrumental effects which are typically 'removed' through calibration are the same on the two bands being compared. Since space-borne sensors are known to degrade with time, it is of great importance to be able to calibrate the instrument repetitively in flight on a long term basis, both in terms of the accuracy of the amount of radiance measured (radiometric accuracy) and in terms of the spectral width and position of the measurements.

The estimation of canopy biochemical composition is based on differential absorption. Simulation studies show that the accuracy of the estimated biochemical composition is very sensitive to the radiometric resolution. Thus, high radiometric performances are required, particularly dealing with band to band noise. Taking the AVIRIS experience, signal to noise ratio better than 300 or more over bright targets (e.g. 40 - 50% reflectance) in the VNIR should be aimed at.

4.2.5. Temporal Requirements

Because we are dealing with vegetation, most of the information on the processes will come from the temporal changes observed within time periods ranging from weeks to several years. The vegetation cover may exhibit noticeable changes over periods of hours or more (e.g., heliotropism, changes in leaf turgor, etc.) but the most noticeable changes that will be tracked by the remote sensing data are certainly the week to week evolution throughout the season. Thus the minimum period between two observations without cloud contamination should not be longer than one week. This will allow efficient assimilation of remote sensing data into dynamic ecosystem functioning models.

In stating the above requirement the important issue of cloud cover needs to be considered. It is well known that on average, half of the Earth is covered by clouds at any one time. To determine the most appropriate revisit period, the requirements of the most demanding application must be identified. In the case of this mission, focusing on biosphere-atmosphere interactions, an effective set of multiple angular views of the surface on a weekly basis would be adequate. Thus a requirement to revisit within one week transforms to a revisit time, in the presence of clouds, to 2-3 days. In summary, a theoretical revisit time of a few days would be adequate for this mission, provided multiple views of the same site can be acquired simultaneously when an opportunity arises.

Spatial Resolution	~ 50 m
Swath width	~ 50 km
Spectral resolution	~10-20 nm + 1μm (TIR)
Spectral range	450 nm-2500 nm, 3-4 μm + 8-12 μm
Re-visit time	~3 days
SNR	>300 (VNIR), >40 (SWIR)
Directional requirements	5-15 view angles

Table 4.1. *Summary of sampling requirements*

4.3. Mission Data Products

The prime data products of this mission are 'top-of-atmosphere radiances' and brightness temperatures, which are geolocated, but not resampled. The scientific users of the data are unlikely to require any other product, and would expect to perform themselves any atmospheric corrections appropriate to retrieve ground level radiances and higher level geophysical products. The data must be available in a timely fashion, but not in real time, as the observations can be used to assist in the planning of all the other observations, particularly in intensive field experiments.

It is expected that the availability of these high resolution data will stimulate the development of new tools and techniques by the scientific community, and that these new methods will be exploited by different entities in a large number of applications.

5. Mission Elements

5.1. Mission Operation

The proposed system will be acquiring detailed information at high spatial, spectral and directional resolution for a limited series of well selected sites, in support of detailed local studies and field campaigns and meeting certain criteria referred to below.

In addition, the instrument could be used for unusual and unexpected events, such as natural disasters, where it would be of great interest to be able to acquire detailed data for damage assessment.

There are essentially three groups of users for the data. The first consists of those scientists working on sites which are being observed for long periods of time, such as the IGBP terrestrial transects, or on dedicated calibration sites. The imaging of these sites would form a background mission to be carried out routinely when it doesn't conflict with higher priority data acquisitions. The second group of users consists of those working on shorter term experiments that, unlike the IGBP transects, are not yet known and where activity will last for a few weeks to a few months; these include experiments such as FIFE or HAPEX, but might include smaller scale operations. These two groups are driving the mission. The third group of users are the governments and international agencies who would be the main customers for sporadic acquisitions. We might call these observations the exceptional mission. It would therefore be highly desirable to be able to operate this system in such a way that (1) a background mission provides systematic data acquisitions over a small number of essential sites (calibration sites, IGBP transects) (2) the principal mission ensures repetitive coverage of a second series of sites where field studies are being carried out, during the relevant experimental period, and (3) additional temporary but high priority missions could be accommodated, to visit additional sites on short notice.

It is assumed that the location of sites to be included in the background mission will be decided through peer review by a science panel, preferably established within an international initiative such as the IGBP. A similar group will meet at regular intervals to assess submissions from the second category of user. The principal and exceptional missions would generally take precedence over the background mission, but the criteria and procedures to be used for the exceptional mission will need to be determined with some care so that conflicts with the mission can sensibly be resolved.

Simulations involving the superposition of global Earth cloud maps, extracted from the International Satellite Cloud Climatology Project (ISCCP), on the swath coverage, show that if an arbitrary site is revisited daily, there is a probability of 78% that a clear view of this site can be obtained by the third day. However, even after 10 days of observation, there would still remain up to 4% of the land surface which would not have been observed under clear conditions.

To obtain a regional cloud climatology to simulate the effect of cloud observation of the land surface for regional coverage requires the use of more sophisticated approaches than the use of statistical models of global cloud coverage referred to above. These regional climatologies should not only predict the presence of clouds but also enable the most important atmospheric optical properties to be inferred. As an example, the coverage of the western part of the Mediterranean area in the spring has been assessed. Meteosat radiometer images from 1984 have been used to compute representative atmospheric transmission factors, T. The percentage of the surface providing an atmospheric transmission factor T of: $T > 0.75$, $0.75 > T > 0.65$ and $0.65 > T$, are presented in table 5.1.

Image quality/ Operation period	$T > 0.75$	$0.75 > T > 0.65$	$0.65 > T$
3 days	87%	5%	7%
5 days	93%	2%	5%
8 days	95%	2%	3%
12 days	98%	1%	1%

Table 5.1. *Percentage of area exhibiting certain atmospheric transmission factors after different observation periods, in the Mediterranean area*

From these statistics it can be seen that, in the absence of clouds, the potential lower transmission factors will not generally inhibit the routine utilisation of remote sensing data for the Mediterranean area.

These constraints suggest the design of data acquisition system where the instrument could be pointed in pre-defined directions where and when appropriate, i.e., when the sites of interest are actually located in cloud-free zones. The optimal use of the instrument should therefore allow the determination of the sites to be observed at the latest reasonable time before data acquisition, taking into account the predicted cloud cover situation.

A further reason to avoid cloud covered sites is that the pointing operations require some time to move and stabilize on the target. If this ‘dead time’ can be eliminated for unnecessary cloud covered areas, then another potential target could be acquired. There will also be some data acquisitions requested at short notice in response to natural disasters. For these reasons the programming of targets should be flexible and able to respond to changes in a short time.

For routine observations ERS satellites are programmed for data acquisitions with a minimum of two weeks notice. In exceptional cases, this period can be drastically shortened. In view of the specific constraints on optical sensor operation due to cloud cover a mission can be designed, where predicted cloud cover estimations from various sources could be used to influence the programming of the instrument at short notice, thus reducing the programming time from ERS's two weeks to a matter of days, and creating a more efficient use of the instrument.

5.2. Interactions with other Missions

The mission is seen as being complementary to a number of existing programmes, and there are possible synergies with other types of instrument.

5.2.1. LSPIM and Active Radar Systems

Active radar instruments form part of a number of planned Earth Observation missions. Interpretation of active radar systems over the land surface is difficult, since few useful models exist for the scattering of radar signals from the land surface. Backscatter cross sections are determined both by surface geometry (canopy structure, microtopography), and the dielectric properties of the surface, which depend mostly on water content. With SAR data alone (especially from monofrequency non-polarimetric instruments) it appears difficult to separate these two effects to infer anything about either structure or surface moisture content.

Data from the LSPIM on plant structure and condition will be very helpful in improving retrievals from SAR instruments. Similarly data from SARs are likely to provide additional information on land-surface processes, for instance on flood extent. From a scientific and mission point of view both facilities should not be flown on the same platform as their observations could not then be used in a synergistic way due to the different observation geometries. It is assumed that a SAR will be available from another mission. The SAR therefore assumes the status of an auxiliary data source to the core of the mission, which is helpful, but not essential to the performance of this mission.

5.2.2. Contributions from other Observations

The prime mission of the proposed instrument is to acquire high resolution data over particular sites simultaneously observed locally by scientific teams in the framework of intensive field campaigns. Many secondary missions, gathering data over agricultural field trial areas, for example, will similarly be operated for groups who would be expected to collect whatever auxiliary data are needed for successful use of the data. Most users acquiring data under the exceptional mission are unlikely to be interested in precise estimation of surface fluxes. Therefore the only part of the overall mission where auxiliary data would be needed to make best use of the data, but are otherwise not provided by users, is likely to be the background mission.

5.2.3. Contributions to other Satellite Missions

This mission has much to offer other satellite missions, particularly those concerned with Earth Radiation Budget studies. The synergistic use with SAR has already been mentioned. Other benefits to accrue to other missions will arise from the ability of this mission to generate BRDF surface information which, with the complete reflectance spectrum extending to the near-infrared, spectral and total albedo can be characterised over different surfaces. One use for this information is in studies designed to relate the inferred albedo for different cover types against the nadir radiances in selected bands, so leading to improvements in the utility of data from radiation budget instruments. Perhaps the most important optical instrument which the Land-Surface Processes and Interactions Mission is complementary is the Multi-angle Imaging Spectro-Radiometer, or MISR. MISR is a NASA instrument due to fly on the EOS-AM platforms.

Major advances in the understanding of the problems of radiation transfer in the atmosphere and at the Earth surface, as well as in the exploitation of remote sensing data in practical applications are expected from instruments capable of observing the targets of interest from different angles. As stated above, it is well known that the radiance field emerging from the coupled surface-atmosphere system at the level of the satellite is anisotropic. This implies that the values of the measurements acquired with all instruments depend, often rather strongly, on the particular geometry of observation and illumination of the scene of interest. These effects have so far been ignored in the exploitation of existing remote sensing data, mostly because of the lack of data to document this issue, but also because of the complexity of actually extracting the relevant information from the data when it is available (for instance when accumulating data with existing instruments over a long period of time). In fact the availability of a new generation of spectral and directional instruments will not only open significant new opportunities to characterise the atmosphere and the underlying surface, but also give the opportunity to add value to the large data bases of existing data, and also to allow the re-analysis a posteriori of the evolution of our environment over the past 20 years of so, once these angular effects have been taken properly into account. A similar synergy will be provided by LSPIM for scientific and operational users of AATSR measurements.

5.3. Ground Data

As already discussed, it is expected that the land processes instrument will be primarily used by teams of scientists who will gather whatever ancillary data are needed to make best use of the instrument data.

The LSPIM requires no specific ESA network to support it, such as buoys, weather stations or corner cubes. The auxiliary meteo data are assumed to be available from established sources (see section 5.2.2).

Extensive ground truth data will be collected by the users themselves as part of their activities on dedicated sites. A description of the use of this data is given in the following section.

For commissioning of activities, campaign data will need to be collected, making use of the infra-structure of the land user community and the ESA experience built up over the ERS and Envisat activities. The magnitude of vicarious calibration activities are the subject of ongoing studies and will depend on the number of calibration tasks performed by onboard calibration hardware. Vicarious calibration activities, as with commissioning phase activities should use the infrastructure established by the LSPIM user community.

5.4. The Users

The data from the LSPIM will be used to improve process parameterisation in key areas of the globe. These areas will be either:

- areas which are uniform spatially and are representative of larger biomes (eg boreal forest)
- areas of transition, where strong gradients occur, such as the Sahel, or regions with highly variable topography. Such areas help us understand the distribution of observed biotopes
- areas under intense human pressure, where rapid temporal changes are known to be taking place (e.g. areas of tropical deforestation; areas with major irrigation projects, such as Sechuan and Gansu areas of China)
- areas of intense ground observation as part of scientific field experiments. Experiments of this kind are listed in Table 2.1.

This mission will be neither a mapping mission nor a mission to compile global data sets. It is therefore synergistic with instruments that have a global mapping objective.

The users therefore are:

- scientists involved with improving land-surface processes models for characterising global changes.
- scientists involved with adding value to EO mapping data, such as from SAR, SPOT, etc., for a wide variety of user applications in areas covered by vegetation (agriculture, forestry, etc.).

Many of the ultimate users of the observations from this mission will be in government, with policy interests in global change, meteorological extreme events, agriculture or water resources.

The LSPIM is timely because of the recent breakthroughs in the retrieval of surface BRDFs, improvements in the parameterisation of land-surface processes because of the series of land surface experiments noted in Table 2.1, and because there will be complementary, coarser observations from MISR on the EOS-AM platform. This Land-Surface Processes and Interactions mission needs to be done contemporaneously with, or soon after, the MISR flight in order that the scientific value added by this mission can be put properly in its global context.

The aim of the LSPIM is to increase the understanding of biophysical processes and land/atmosphere interactions at the local scale exploiting the increase in knowledge of (small scale) processes and to advance the understanding of these interactions on a global scale. A limited lifetime data set of a few years would create a sufficiently large database covering a broad range of ecosystems to achieve this advance of understanding.

5.5. Space and Ground Elements

The space based elements of the mission are clearly derived from the observational requirements. A single satellite is proposed with a main imaging spectroscopy instrument able to provide the required observations in the visible and in the infrared.

Coverage requirements can be met by a proper design of the orbit profile, the satellite and its payload.

The ground segment will include the following elements:

- a command and data acquisition station at suitable high latitude in Northern Europe with the tasks to receive the data and process them to level 0 and to establish all communication links with the satellite;
- a mission and satellite control element;
- a processing and archiving element that processes the data to level 1b and disseminate them to the users.

6. System Concept

6.1. General

The observation requirements described in chapters 4 and 5 clearly identify the main characteristics for the space segment of this mission:

- geometric and temporal requirements can be met by a single satellite mission designed to provide the required accessibility and revisit characteristics;
- a single hyperspectral imaging instrument, later referred to as the PRISM (Processes Research by an Imaging Space Mission) instrument, can be defined with the capability to provide observations of the required spectral, radiometric and directional characteristics.

PRISM is necessarily a high data rate instrument. This requires some care in the definition of the mission data flow. The mission however shares some of the requirements typical of missions such as SPOT, ERS and ENVISAT. The scientific nature of the mission, and in particular the absence of near-real-time data dissemination requirements will allow us to reuse much of the experience and resources acquired during the ERS and ENVISAT missions.

In short, the space segment for the Land-Surface Processes and Interactions Mission will be characterised by:

- a single satellite in a near-polar orbit capable of supporting the mission data flow generated by the payload and of enabling the payload to access all land areas with the required geometric and temporal characteristics;
- an hyperspectral imager, which will be the main satellite payload, with the required spatial and spectral resolution covering the optical range of electromagnetic spectrum with good radiometric accuracy and with the capability to perform directional measurements;
- auxiliary instrumentation: as a baseline, the auxiliary instrumentation includes only a navigation receiver GRAS (GNSS Receiver for Atmospheric Sounding), which will provide precise location and datation information useful for PRISM data processing. The auxiliary instrumentation could also include a simple imager with a few spectral bands specifically for BRDF measurements, should future studies show that BRDF measurements with PRISM lead to excessive instrument complexity.

The following sections in this chapter will describe the main system elements:

a) the main on-board instrument, PRISM, will be described in detail in 6.2; the GRAS instrument is not addressed here as details can be found elsewhere (ESA 1996);

b) the mission and operations profile is described in 6.3, where the rationale for the choice of orbit and attitude requirements is provided;
c) the concept elaborated so far in the preliminary studies for the spacecraft design using a medium class satellite platform is outlined in 6.4, where the basic system budgets are provided;
d) finally, a possible preliminary concept for the ground segment and the data processing is defined in 6.5.

The main purpose of this chapter is to demonstrate that concepts exist for the payload, the spacecraft and the ground segment designs.

6.2. The Payload

6.2.1. Objectives and Principle of Operation

The objective of the PRISM instrument is to produce sets of spectral images of selected Earth sites, measured simultaneously in different wavelength regions. Each spectral image is a 2-D array of samples made of an equal number of rows and columns. All spectral images of a set have the same number of rows and columns. The spectral images of a set need to be tightly coregistered both spatially and spectrally, for accurate exploitation of data. This means that the centres of the corresponding picture samples of all spectral images should be coincident. In the spectral domain, it is required that the picture samples of each spectral image contain the same spectral information. The instrument will cover two main wavelength regions, which will be called hereafter region 1 and region 2.

Region 1 covers the Visible-Near InfraRed (VNIR) and the Short-Wave InfraRed (SWIR) from 0.45 to 2.35 μm. In this region the instrument works as an imaging spectrometer with a spectral resolution of about 10 nm. region 2 covers the Thermal Infra-Red (TIR) range from 8 to 12.3 μm, divided into 3 spectral bands with a typical width of 1 μm.

The physical parameters directly measured by the instrument are top of the atmosphere radiances of the selected ground sites. The images will be calibrated to assign an absolute radiometric value to each of its picture elements. The instrument will acquire images by the 'pushbroom' method, meaning that a region on ground is imaged on linear detector arrays which provide the required field angle and spatial resolution in a direction perpendicular to the satellite motion (across track). The along track scan is provided by satellite motion.

The spatial resolution at nadir is about 50 m over a swath (image size) of 50 km. The PRISM instrument is designed to be flown in a polar sun-synchronous orbit and features pointing capability for convenient accessibility of selected Earth sites.

6.2.2. Instrument Requirements

Drawing on the earlier discussion, the specifications of a system addressing the requirements for a Land Surface Processes and Interactions Mission are as follows:

POINTING REQUIREMENTS	
Across-track range	± 475 km ~ ± 30°
Across-track step	5 km ~ 0.36°
Pointing accuracy	0.05 ° on all axes
Pointing stability	0.002 °/s

SPATIAL REQUIREMENTS	
Swath width	50 km
Spatial sampling interval	50 m
Spatial registration within region 1 and region 2	< 0.2 spatial sampling interval
System Point Spread Function (PSF)	< 1.75 spatial sampling interval

SPECTRAL REQUIREMENTS	
Spectral range region 1	0.45 - 1.11 µm 1.16 - 1.40 µm 1.49 - 1.79 µm 2.02 - 2.35 µm
Spectral sampling interval	< 15 nm (Goal : 12 nm) < 10 nm in range 680 ÷ 769 nm
Spectral registration	< 0.15 spectral sampling interval
Centre line accuracy	0.5 nm
Spectral width accuracy	0.5 nm
Spectral range region 2	8.1 - 9.5 µm 10.3 - 11.3 µm 11.3 - 12.3 µm

DATA RATE REQUIREMENTS	
Number of images per orbit	30 daytime and 30 night time
Acquisition modes	– Full spectral and spatial – Spectral selection
Max. number of consecutive images	3

RADIOMETRIC REQUIREMENTS	
Signal dynamic range in region 1	Specified Max. and min. radiances
Signal resolution in region 1	12 bit
Absolute radiometric accuracy in region 1	Goal : $< \sqrt{(NEdL^2 + 0.02\ L^2)}$
Radiometric dynamic range in region 2	200 - 360 K
Radiometric resolution in region 2	NEdT < 0.1 K
Absolute radiometric accuracy in region 2	1 ÷ 3 K
Polarisation sensitivity	< 0.03 λ=450 nm < 0.1 λ=700 nm < 0.3 λ=1000 nm

BRDF REQUIREMENTS	
Range observation angle (along-track)	±70, ±60,±45,±30 degrees
Spectral bands	0.5, 0.65, 0.85, 1.6, 2.2, 10.3-11.3, 11.3-12.3 μm
Spectral sampling	10 - 50 nm
Radiometric range and resolution	Spectrally defined values
Spatial sampling and swath	50 m , 50 km
Relative accuracy of image set	2%

6.2.3. The PRISM Concept

The PRISM instrument concept combines the main features of a visible and short-wave infrared imaging spectrometer and a thermal InfraRed imaging radiometer. In order to establish a feasible design of such an instrument, ESA initiated two parallel studies in 1994. These studies reached their conclusions in October 1995 and both produced a feasible conceptual layout fulfilling the requirements within the given system constraints. In the following description we will refer to the two conceptual layouts as concept A and concept B (figure 6.1a and figure 6.1b).

Both designs are based on a pushbroom type of imaging spectrometer in which the entire field of view is imaged on detector arrays. The pointing optics, which allows the instrument field of view to be pointed so as to access selected observation sites on the earth, and the telescope, which images ground scenes on the detector arrays, are in both designs common to the entire wavelength range.

The reflectance channels (450 - 2350 nm) and the thermal InfraRed bands are in-field separated by means of separate slits in the focal plane of the telescope. Within the thermal infrared range, dichroic filters and relay optics are used to image the field on separate linear

Mercury-Cadmium-Telluride (MCT) detector arrays operating at about 50 K. The detector arrays are cooled using Stirling-cycle mechanical coolers.

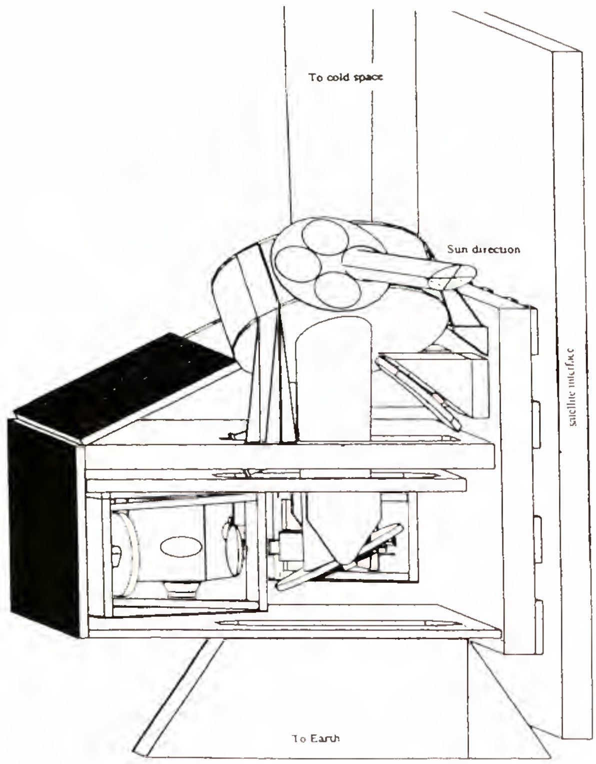

Figure 6.1a. *Overall architecture of the PRISM instrument - Concept A*

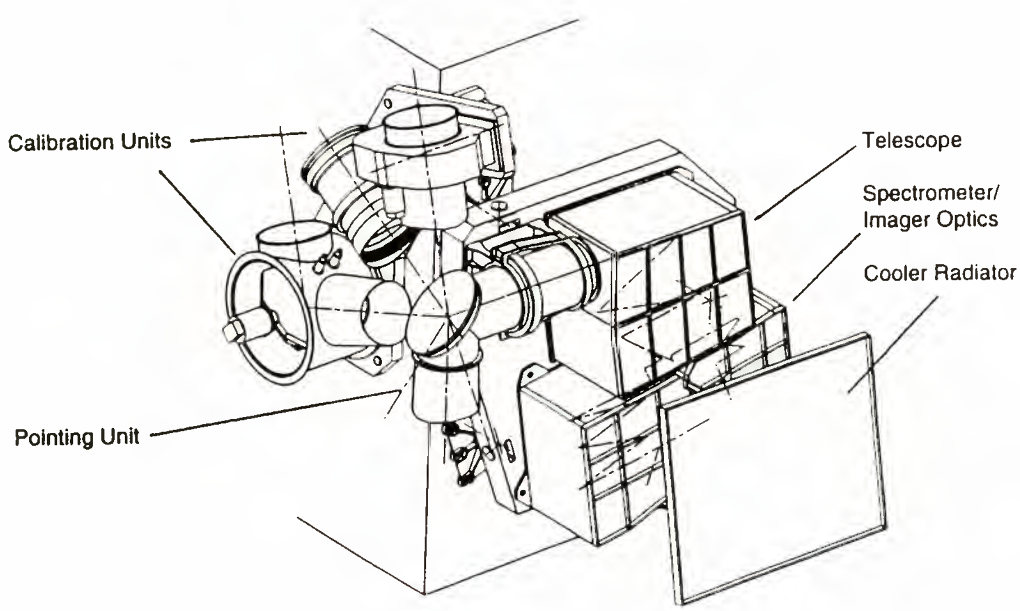

Figure 6.1b. *Overall architecture of the PRISM instrument – Concept B*

In both designs a single spectrometer is employed to split the visible and shortwave infrared range into the desired number of bands. A dichroic filter is then used to serve two focal planes based on a Silicon CCD detector array (450 -1000 nm) and a MCT detector array (1000 - 2350 nm) operating at about 150 K. InGaAs detector arrays have been also considered for the 1000 -2350 nm range.

The in-flight radiometric calibration is performed using aperture plates, solar diffusers and black bodies. The implementation and arrangements of the calibration devices has proved to be a major design challenge; the different solutions adopted for the two concepts will be described.

A functional block diagram of the instrument is shown in figure 6.2.

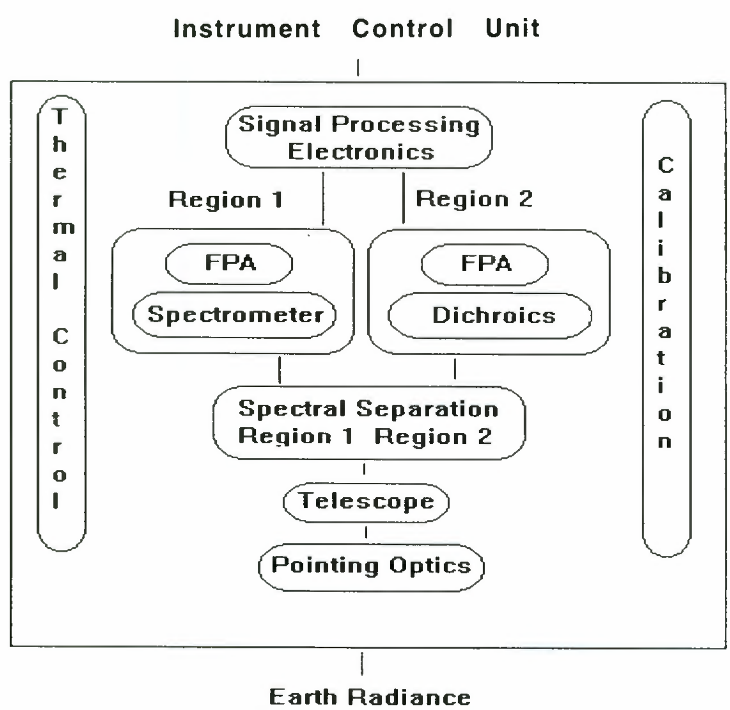

Figure 6.2. *Functional block diagram of the PRISM instrument*

6.2.4. Subsystem Description

Pointing Optics

The instrument pointing requirements are achieved by means of a rotatable flat mirror located outside the instrument imaging optics. Other methods for deflecting the instrument field can be considered, such as satellite rotation or rotation of the entire instrument. There are usually two kinds of rotation which can be applied to a mirror: a rotation about an axis parallel to the axis of the reflected beam ('in beam' rotation) and a rotation about an axis lying in the plane of the mirror ('in plane' rotation). They are shown schematically in the first two diagrams of figure 6.3.

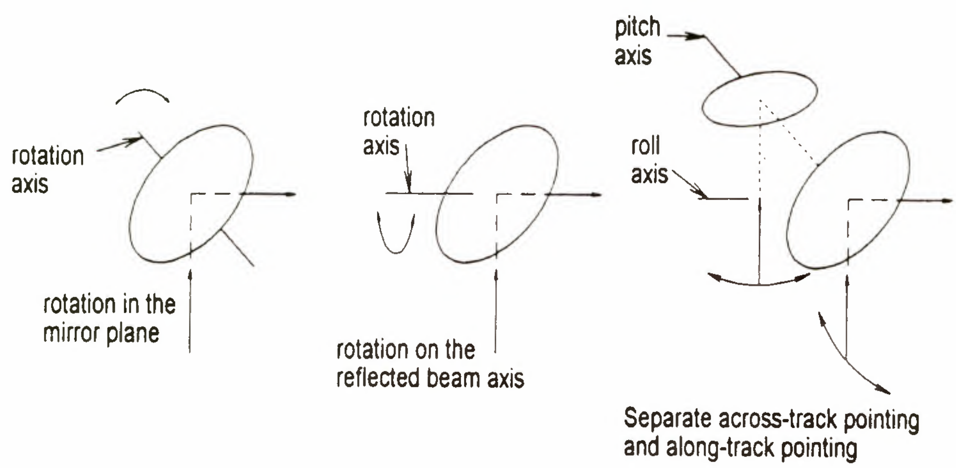

Figure 6.3. *Single axis pointing options for the PRISM instrument*

The in plane rotation has the substantial advantage that it does not introduce a rotation of the reflected image, and therefore the footprint on Earth of the detector arrays is always orthogonal to the velocity vector. As a consequence of this:

- the shape of each image is approximately square,
- it is possible to use staggered arrays or two dimensional arrays with time delay integration methods to register successive rows of element images in the TIR.
- in-field separation can be employed with minimal misregistration of the separated channels.

On the other hand the main disadvantages of the in plane rotation are :

- the angle of incidence of the beam on the mirror changes with mirror rotation, so that in general the reflectance of the mirror changes with pointing angle. Although this can be

calibrated on ground, it is likely to change in orbit due to contamination over the mirror surface,
- the pointing range is limited to two ranges of about 60 degrees around nadir and 90 degrees around zenith,
- the mirror tends to have fairly large dimension for the required pointing range and therefore cannot be baffled very efficiently against light received from ground.

The main disadvantage of the in beam rotation is that it produces image rotation equal to the rotation angle. Thus, in deflecting the field at the extreme of the across-track direction it will produce a rotation of the arrays footprint on Earth of 30 deg respect to the velocity vector. This effect prevents the use of staggered arrays or TDI techniques because it leads to loss of resolution and non constant sampling interval. Linear arrays are required for this option. Other disadvantages are that the image shapes will be sheared and in-field separation introduces larger image separation.

On the other hand the advantages of the in beam rotation are:

- the angle of incidence of the beam on the mirror is constant with the pointing angle, so that no errors are introduced due to uncalibrated changes in reflectance with pointing direction
- a large angular range can be achieved, in principle a continuous 360° range, which would make easier the access to external characterisation sources and possibly extend the feasible pointing range of the instrument
- it has smaller dimensions
- can be very efficiently baffled

An additional advantage of the in-beam option is that it can be developed to provide two-axis pointing capability, as indicated in the third diagram, in fig. 6.3. If the main pointing mirror is rotated by 90° from nadir as shown, it can receive the beam reflected from an identical rotating mirror which receives the beam from any selected direction in along-track plane. The instrument can thus have along-track pointing capability, as well as full across-track pointing in a plane through nadir.

Telescope

The telescope is the most straightforward optical subsystem of the entire instrument. Both studies have chosen as baseline a three mirror anastigmatic telescope, which is a variant of the current version bread boarded in the frame of the ongoing technology programme. The main features which make this configuration very attractive are a very good image quality, a compact size and the availability of a real entrance pupil which can be located at the position of the pointing mirror to minimise its dimensions.

Spectral Separation between Region 1 and Region 2

The separation of the two main spectral domains, region 1 and region 2, is achieved in both concept A and B, by means of in-field separation. This arrangement implies that the corresponding detectors in the two regions have different footprints on ground which are shifted with respect to each other. Spatial coregistration in the along track direction is then achieved by a time delay in image acquisition. The in-field separation is accomplished by means of an optical device, which reflects one beam, while the other is transmitted through a slit, which is usually the entrance slit of the following spectrometer.

Region 1 Optics

The splitting of individual wavebands in region 1 is achieved in both conceptual designs, by means of a single spectrometer. A dichroic beam-splitter is then used to serve the VNIR and SWIR Focal Plane Assemblies. The difference between the two baseline concepts is in the design of the spectrometers. In one design, two off-axis Schwarzschild telescopes, which function as collimator and imager, are employed in conjunction with a single disperser used in double pass. The other design is based on an Offner type relay, operating at unit magnification, with the dispersive element made up of three cemented curved prisms. Both designs show good performances, especially concerning spatial and spectral misregistration. One of the main features of both spectrometers is a non constant spectral sampling as a function of wavelength. This feature has an impact on VNIR and SWIR focal planes where on chip summing of pixels is required to achieve an almost constant spectral sampling.

Region 2 Optics

After in-field separation the beam corresponding to region 2 is further split down into the required number of bands, by means of dichroic beam-splitters serving different Focal Plane Assemblies, all located in a single common cryostat. This arrangement is common to the two concepts, as also is the use of an all reflective optical system to re-image the ground scene onto different detectors.

Focal Plane Assemblies

VNIR – The baseline detector for the visible and near infrared range is a thinned silicon CCD array. To meet the radiometric requirements, back-illuminated geometry will be preferred in view of the higher quantum efficiency. This array will be a custom tailored one with a pixel size of 30 x 30 μm, showing some similarity with the MERIS CCD. One of the most important features is that it will be possible to perform on-chip summing of a certain number of adjacent spectral lines. This is needed because of the non uniform spectral dispersion of the spectrometer described before. The spectral over sampling will also help to avoid over saturation when looking at high reflectance ground scenes around 700 nm. The array size will be approximately 200 × 1000 pixels, provided with four separate frame transfer areas to reduce read out frequency.

SWIR – The detector baseline for the Short Wave infrared range, is a 2-D array of photovoltaic Mercury Cadmium Telluride (MCT). Four sub-arrays of 256 pixels each, are butted together in order to achieve the required number of pixels in the spatial direction, and than hybridized via a Mosfet injection stage onto a Silicon CMOS Multiplexer. Each sub array is fitted with two output stages. The pixel size is 30 × 30 μm, and the array size is approximately 140 × 1000 pixels. This array is presently the subject of breadboarding activities in an ongoing technology development programme. First results of these activities have shown that the arrays exhibits a small non linearity in response over its mid dynamic range, entailing that a calibration at different radiance level might be necessary. Some attention was also devoted to InGaAs detector arrays, which show some interesting features such as an higher operating temperature compared to MCT (180 K vs. 150 K), thus allowing only passive cooling, and the possibility to optimize the detector response as a function of wavelength for different sections of the array. However, the main drawback is that this technology is not mature yet above 2μ, and consequently its performances in that region are still uncertain.

TIR – Baseline detectors for the region 2 spectral channels are linear arrays of photovoltaic Mercury Cadmium Telluride (MCT). Also in this case, for each spectral channel, four linear sub-arrays of 256 pixels each, will be butted together to achieve the required size in the spatial direction, and hybridised on a Silicon multiplexer. Each array will be fitted with two video output stages. The preferred array topology will probably be based on linear (i.e. non-staggered) geometry both for pixels and for sub-modules. This is related to the occurrence of image rotation generated by the pointing optics as outlined above.

Cryostat and Coolers

The focal plane arrays covering the wavebands in region 2, are all assembled in the same cryostat operating at a temperature of about 50 K, which is dictated by the thermal infrared band. The only solution to achieve this temperature is by means of active cooling. Therefore the baseline design includes closed loop 50-80 K mechanical coolers, arranged in a back-to-back configuration to minimize vibrations. Both compressors and displacers are mounted on a mechanical structure which is decoupled from the optical bench.

Calibration

Both concept A and B make use of characterisation hardware to accomplish in-flight calibration of both region 1 and region 2 of the PRISM instrument. Although slight differences occur in the calibration scheme and philosophy, the implementation and arrangement of the characterisation hardware is substantially different for the two concepts.

Concept A

The baseline design of the characterisation hardware includes three main subunits. The physical location of these subunits within the instrument depends upon the choice of the rotation axis of the pointing mirror. The study team which produced concept A retained the in-beam rotation and the in plane-rotation at the same level of preference.
The main subunits are:

- A shutter wheel which incorporates a hole, a sieve plate for medium radiance calibration, a filter for spectral calibration and a shutter.
- A diffuser wheel supporting a hole, a solar diffuser used frequently and a second diffuser used less frequently
- A pair of small black bodies coupled to an imaging mirror to calibrate region 2 upper radiance level and gain

The shutter and the diffuser wheels work in combination to cover different ranges of radiances. In particular, the shutter allows determination of the dark current level in region 1, while the hole and the sieve plate in the shutter wheel combined with the diffuser allows characterisation of high and medium radiance ranges respectively. Wavelength calibration is achieved by simultaneous use of the filter and the diffuser. The second diffuser is used less frequently and its main purpose is to characterise changes in the reflectance of the first one due to in-orbit ageing. The lower radiance levels as well as the optics background radiance are determined by means of frequent cold space views via the pointing mirror through the holes present in both the shutter and diffuser wheel. Calibration against the sun is performed over the North Pole.

Concept B

The baseline concept for calibration of both region 1 and region 2 comprises three main subunits mounted on the calibration panel attached to the platform in anti-flight direction. These subunits are:

- A plate with a pattern of small apertures for absolute calibration of region 1 against the sun. This allows to calibrate about 100 pixels of the total field of view.
- A full-aperture sun illuminated diffuser for relative calibration of the total field of view in region 1. In order to perform gain calibration, the same subunit also support a rotating drum shutter by which reduced radiance levels are attained in almost continuous steps. Absolute wavelength calibration is performed by means of 2 laser diodes mounted on the same structure of the solar diffuser. One diode is used to calibrate the VNIR range and the other diode to calibrate the SWIR range.
- A full aperture IR black body which allows determination of both dark current in region 1 and upper radiance level in region 2. The black body temperature can range from 260 to 310 K, with occasional heating up to 360 K, for gain determination in region 2.

The lower radiance levels as well as the optics background radiance are determined by means of frequent cold space views via the pointing mirror directly. An additional internal small reference is also accessed frequently via a small flip mirror before and after each imaging acquisition, in order to calibrate for short term drifts in dark current level of band D. The aperture plate and the sun illuminated diffuser require both an unobstructed field of view towards the sun. Calibration against sun is performed over the Equator.

Electronics

A preliminary electrical architecture of the PRISM instrument is shown in figure 6.4.

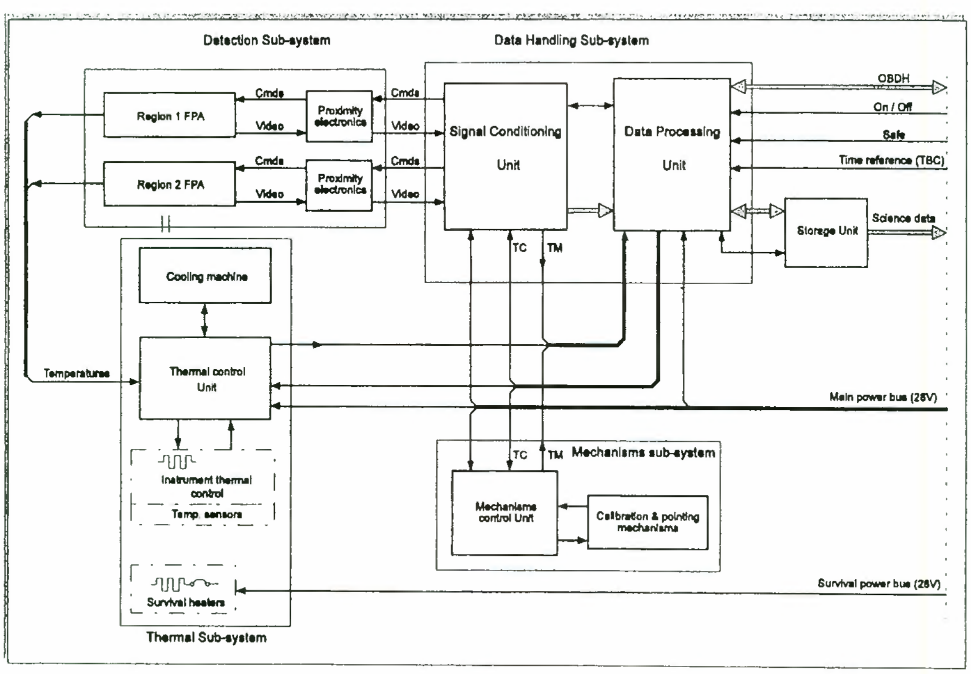

Figure 6.4. *High level electrical architecture for the PRISM instrument*

6.2.5. Performance

Radiometric Performance

Figure 6.5 shows radiometric performance estimates in region 1, in terms of Signal to Noise Ratio. The calculations include realistic variations of the spectral sampling interval, produced by the prism spectrometer. As can be readily seen, performances achieved both in VNIR and SWIR in terms of SNR are well within the given requirements. In region 2, the requirements for radiometric resolution and spatial radiometric accuracy are set at 0.1 K for all bands. Requirements are achieved for all bands.

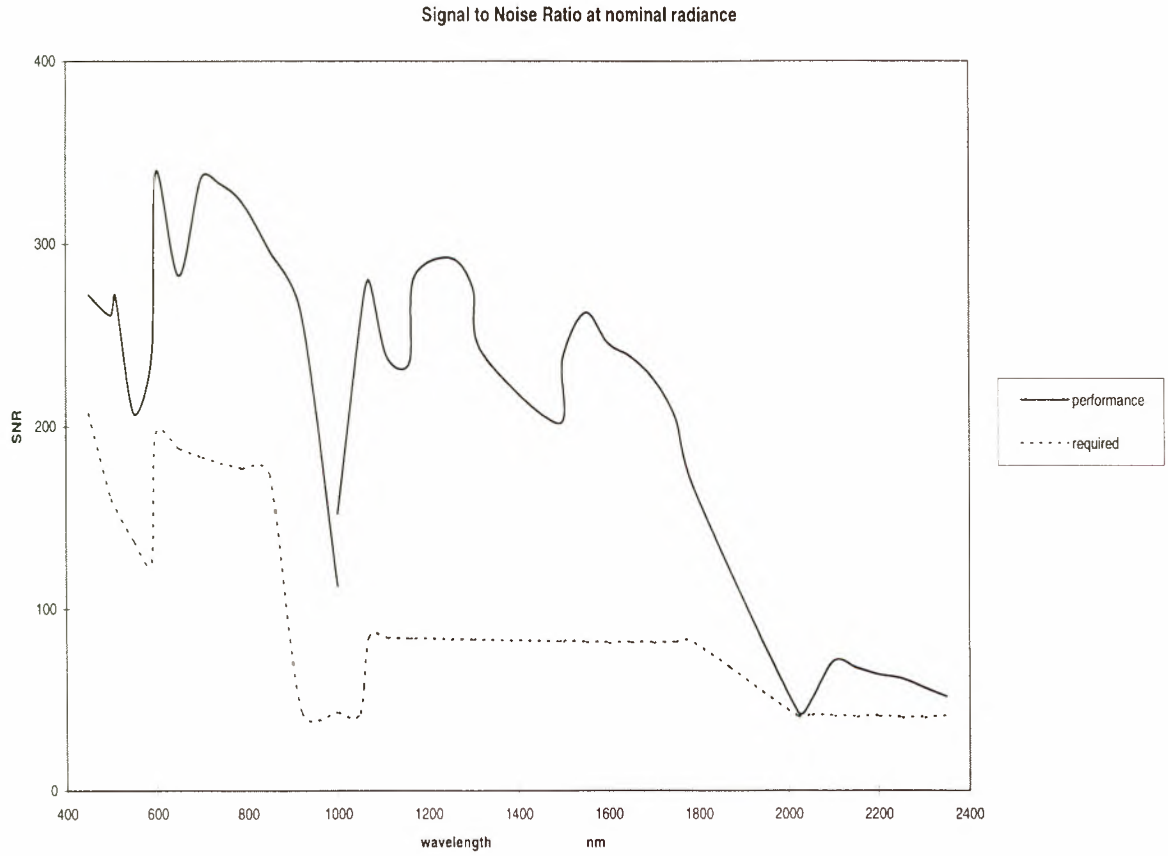

Figure 6.5. *Signal to noise ratio of the PRISM instrument for nominal radiances*

Spatial Performances

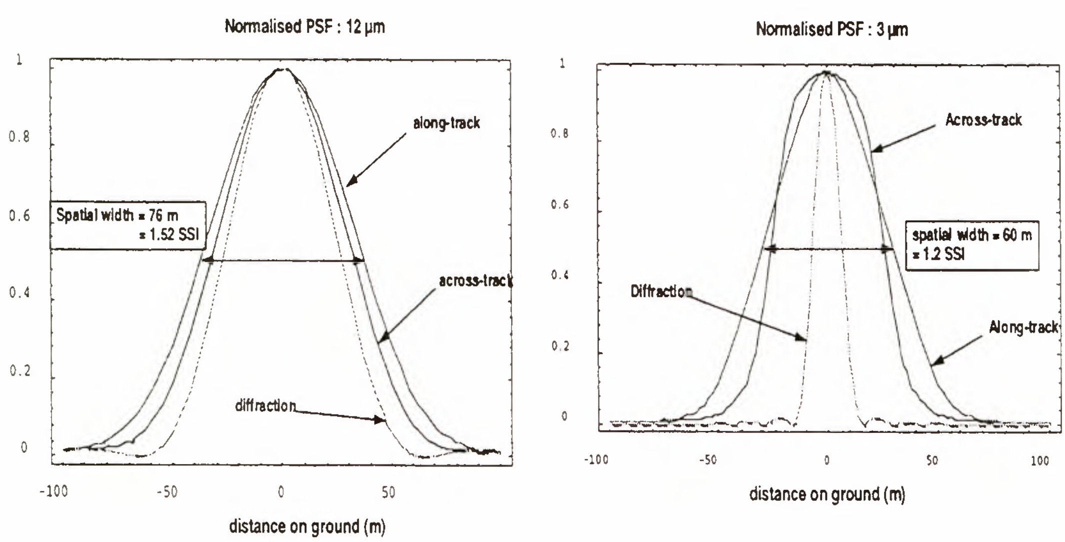

Figure 6.6. *Geometrical performance of the PRISM instrument. The overall point spread function is shown for two different wavelength ranges*

Figure 6.6 shows the calculated PSF of the entire instrument. The calculation includes effects due to diffraction of the optics, both telescope and relays, manufacturing defects and geometrical aberration, detector geometry and, in along track direction only, smearing due to motion. The PSF is compliant with the given requirements, being smaller than 1.75 spatial sampling interval for all bands.

Spectral Performance

Both spectrometer concepts show compliance with the given requirements in terms of spectral sampling. Spectral and spatial coregistration are also within the given requirements, with maximum misregistration of 0.1 spectral sampling interval.

6.2.6. Budgets

The preliminary budgets for the PRISM instrument lead to a total instrument mass of approximately 375 kg and to a total power of 430 W. Both values include a 10% margin.

6.2.7. Heritage

The PRISM instrument basically combines the main features of two instruments which were previously studied by ESA, the High Resolution Imaging Spectrometer (HRIS) and the High Resolution Thermal Infra-red Radiometer (HRTIR). The main goal of these studies was the assessment of certain critical technological issues. Because of the applicability of these technologies to the PRISM concept, hardware developments have started and preliminary results look promising. In particular, a complete optical chain consisting of a telescope, quite similar to the one envisaged for PRISM, and a double spectrometer is the subject of a breadboarding activity initiated in the frame of HRIS technology studies.

Within the same frame, another important building block for PRISM which is being developed is the realisation of improved MCT detector arrays with a cut-off wavelength near 2.4 μm. A first breadboard of a 128 × 128 MCT array to be used in the 1.0 - 2.35 μm spectrometer has demonstrated the yield, uniformity and performance of the elementary diodes despite the use of a non optimised multiplexer. Improved MCT detector arrays (128 × 140 pixels) with a cut-off frequency near 2.4 μm are being manufactured to demonstrate the noise and linearity performances when hybridised on a customised multiplexer and to test the critical butting techniques used to join sub-modules to realise large arrays.

Linear arrays of MCT detectors with a 12.5 μm cut-off wavelength have been previously demonstrated. This development has shown the performances of the diodes and of the CCD multiplexer, but has also revealed a poor yield at the extremities of the 74 pixel MCT module. The continuation of this technology effort, with an emphasis on the demonstration of longer

MCT modules with a cut-off wavelength above 12 μm, is presently being pursued. The result of the studies of PRISM will help to precisely define the engineering requirements on these detectors.

6.3. Mission and Operations Profile

6.3.1. Mission Profile

The driving requirements for the selection of the mission profile are:

a) access to all land areas;
b) capability to provide images of an arbitrary land area in daylight at intervals of at most three days, assuming cloud free conditions;
c) provision of suitable visibility conditions for the PRISM instrument.

Requirement (a) is easily met by using a (near-polar) sun-synchronous orbit, which, in combination with the across-tracking capability of PRISM, ensures complete access to all land areas.

The three day revisit time capability of requirement (b) implies a proper choice of the repeat period of the sun-synchronous orbit, taking into account the maximum across-track pointing angle achievable by the PRISM instrument, approximately +/- 30 degrees. A repeat period of 32 days has been tentatively selected.

Figure 6.7 shows the required PRISM across-track pointing angle for daylight full Earth coverage at the equator in 1, 2, 3, 4, and 5 days for sun-synchronous orbits at mean altitudes between 400 and 900 km and with repeat period between 1 and 40 days. From this figure, it is apparent that orbits compatible with the +/- 30 degree pointing capability exist with altitudes close to 500 km, 650 km and in the range 750 - 820 km. Since the orbital altitude is not critical for achieving the required PRISM radiometric performance, the analysis has been restricted to the orbits at altitudes between 760 and 790 km.

One suitable orbit has been found at 772 km mean altitude, corresponding to a 32 day repeat period. For this orbit the required across-track pointing angle range is of +/- 30.5 degrees and the mean revisit time is of 43.5 hours. The minimum and maximum revisit times are 1.6 hours and 72 hours (3 days), respectively.

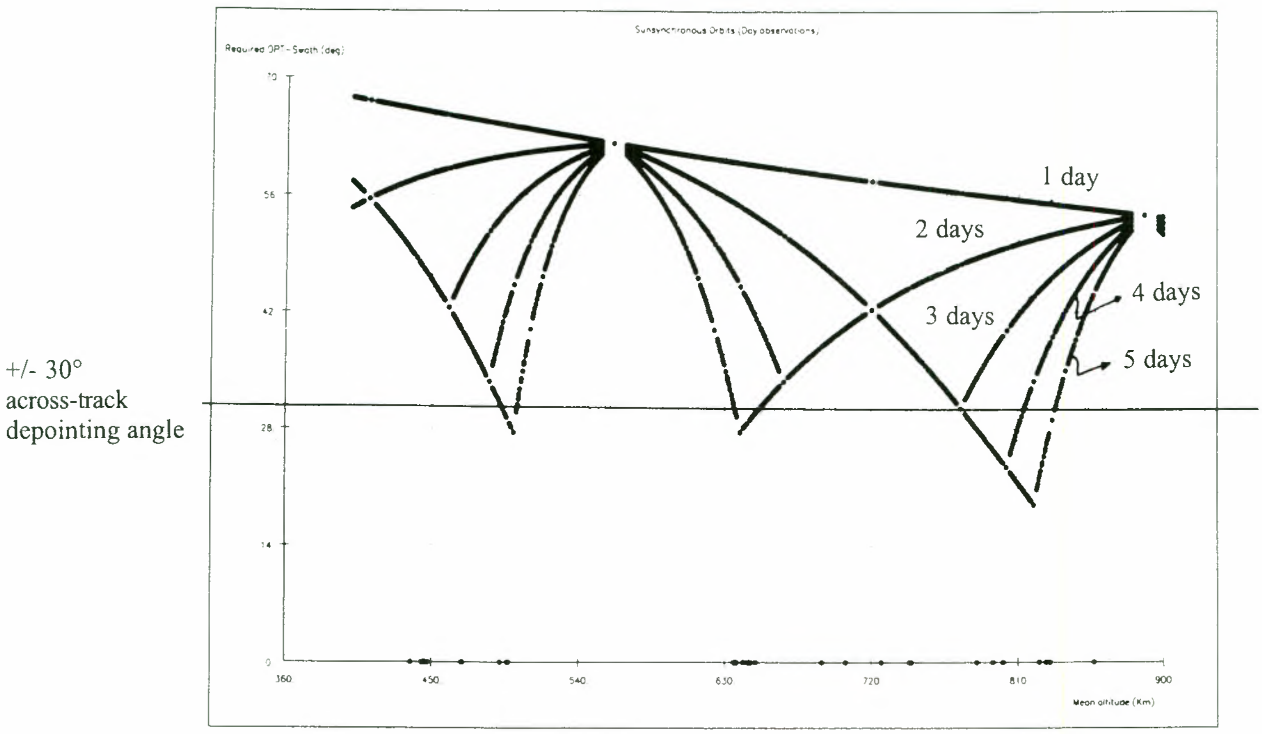

Figure 6.7. *Required across-track depointing angle for a daylight full Earth coverage in 1, 2, 3, 4, and 5 days for sun-synchronous orbits as a function of the mean altitude*

Finally, requirement (c) above results in the selection of a Local Time at the Descending Node (LTDN) equal to 11:00 hours, to provide a favourable sun incidence angle for PRISM imaging. The main orbit parameters are summarized in the Table 6.1 below.

Semi-major axis	7150 km
Inclination	98.5 degrees
Eccentricity	< 0.001
LTDN	11:00 hrs.

Table 6.1.

From the ground segment standpoint, the selected orbit provides a good baseline for data communication and spacecraft control. Assuming the utilization of a single high-latitude ground station, e.g. in Kiruna (S), 10 passes per day can be used for communication. The total contact time for Kiruna slightly exceeds 100 minutes per day. The on-board data storage must however be sized taking into account that up to 5 consecutive orbits can occur without any possibility for data downlink.

An alternative, lower orbit is also under consideration because of the potential scope for optimisation of the PRISM instrument and of the spacecraft. The average altitude for this orbit is of 666 km and the corresponding sun-synchronous inclination is 98.0 degrees. In this orbit the three day access time requirement is also met if the PRISM pointing capability is increased to 33.5 degrees, which appears to be feasible. Ground contact time will however be slightly reduced to about 80 minutes per day.

The pointing requirements of the mission call for both along and across track pointing and can be met by two different design solutions, which are presently under investigation but do not present any feasibility problem:

a) use of the PRISM instrument pointing capability combined with satellite roll/pitch manouvering;
b) use of an additional pointing mirror in the PRISM instrument.

6.3.2. Mission Phases and Operational Constraints

The mission concept would consist of three main phases:

- a Launch and Early Orbit Phase (LEOP);
- a Commissioning Phase, and
- an Operational Phase.

The LEOP is a very short comprising the launch and the acquisition of the nominal orbit and spacecraft attitude. The Commissioning Phase includes the check-out of the spacecraft sub-systems and the first calibration of the PRISM instrument. Its nominal duration is one month.

The Operational Phase lasts four years and ends with the mission end of life. During the Operational Phase the only operational constraints arise from an objective to operate the spacecraft using a single ground station, to minimize cost. Commands are up-linked at each usable contact with the ground station so as to supply the spacecraft with a pre-programmed sequence of observations, which include primary observations.

The operational approach is driven by the requirement to be able to collect at least 30 images per orbit in daylight and as many in eclipse conditions. On-board operational modes will reflect periods when the PRISM instrument is fully operating (image acquisition, lasting about 7 seconds per image), when it is being re-pointed, and when it is idle. This implies an effective instrument duty cycle of about 3.5%. Though PRISM will be in an idle mode for more than 90% of the orbital period, the effective duty cycle is actually larger if one considers that a good fraction of the orbital period cannot be used anyway because the spacecraft is flying over the oceans or over cloud-covered areas.

6.3.3. Attitude Requirements

The nominal satellite attitude in both the commissioning phase and the operational phase is an Earth pointing one, with yaw steering implemented to ensure correct spatial co-registration of different PRISM spectral bands and to correct the pixel line twisting due to the Earth's rotation. The absolute pointing requirement of 2.5 mrad r.m.s. are derived from the PRISM requirement for targeting the instrument footprint. They are not considered to be particularly demanding. The geolocation of the images drives the attitude determination requirement. A value of 2.0 mrad r.m.s. has been defined, which is compatible with a geolocation accuracy of 2.4 km at the edge of the swath (i.e., for 30 degrees across-track scan angle) in the case of a null along-track scan angle. Table 6.2 below summarizes the geolocation error budget, with reference to two cases: (a) when pointing at a 30 degrees across-track angle and 0 along-track angle; and (b) at 0 across-track angle and 45 degrees along-track angle. The impact of errors due to orbit determination and datation are entirely negligible as the position and time information provided by the GRAS instrument are lower than 50 m (maximum real-time error) and 1 microsecond, respectively.

The attitude rate stability requirements are driven by the requirement for 0.2 pixel accuracy in the co-registration of pixels in different PRISM bands. An angular rate stability of 0.1 mrad/s is sufficient to meet this requirement, which is within the reach of present satellites for Earth Observation.

AOCS Pointing Determination Error	2.0 mrad
AOCS/PRISM Alignment Error	0.5 mrad
Instrument Internal Pointing Error	1.0 mrad
Total Pointing Determination (Footprint Geolocation) Error	2.4 km (across-track) 3.5 km (along-track)

Table 6.2.

6.4. Spacecraft

6.4.1. Guidelines and Constraints

The characteristics of the payload for the Surface Processes and Interactions Mission are such that two spacecraft implementation options exist:

- the use of existing large platforms for polar orbiting satellites, i.e. one of the Mark series of platforms used for all large European polar orbiting satellites for Earth observation;
- the use of smaller platforms (in terms of mass, power and volume), currently under study or development under national initiatives in Europe.

The first option has the advantage of the possible heritage in terms of space and ground equipment, including on-board and ground operational software developments. However, a major disadvantage is that a Mark-class platform would be vastly oversized for the Surface Processes and Interactions Mission, with severe penalties in terms of launcher selection and overall mission cost. If such a platform is resorted to, the only available european launcher is the Ariane 5 launch vehicle. Even in the case of a launch shared with another polar orbiting satellite (with an orbit necessarily similar to that of the Surface Processes and Interaction Mission), the launch cost would be comparable to that of the platform procurement. On the contrary, the use of a smaller platform will be more commensurate with a mission mostly dedicated to collecting measurements from a single instrument, and would result in substantial savings in both platform and launcher procurement costs. The total payload mass for the mission will not be larger than about 580 kg, as detailed in Table 6.3 below, where no optimisation of the PRISM instrument has been accounted for.

PRISM Instrument Mass	< 380 kg
GRAS Instrument Mass	< 10 kg
Solid-state Mass Memory	< 100 kg
Data Transmission & Ancillary Electronics	< 60 kg
Structure and Thermal Control	< 30 kg
Total Payload Mass	< 580 kg

Table 6.3.

A total payload mass of less than 600 kg is compatible with an intermediate size platform. Similar conclusions can be derived from the payload power budget.

6.4.2. Configuration and Mechanical Design

As a baseline, the mission will be implemented as an Earth-pointing satellite in a rather conventional orbit with orbital parameters similar to those of ERS-1/2. Two possible spacecraft configurations are shown in figure 6.8 and figure 6.9, respectively. They are both designed to fit within the fairing envelope of the available small/medium class launchers. In both configurations, the PRISM instrument is mounted on the top of the satellite structure. The payload occupies approximately half of the total volume of the spacecraft main body. The X-band high gain antenna for science data downlink and one of the two S-band antennas are located on the nadir pointing side. A second S-band antenna is mounted on the zenith-looking side, so providing an omnidirectional field of view for spacecraft telemetry and telecommand.

The main difference between the two configurations is due to the design of the solar panels, which in one case is based on a single wing, whereas in the other case an arrangement of two wings is preferred. In both designs the planes of the solar panels are tilted by an angle of about 20 degrees with respect to the normal to the orbital plane, so as to ensure adequate solar illumination conditions for power generation.

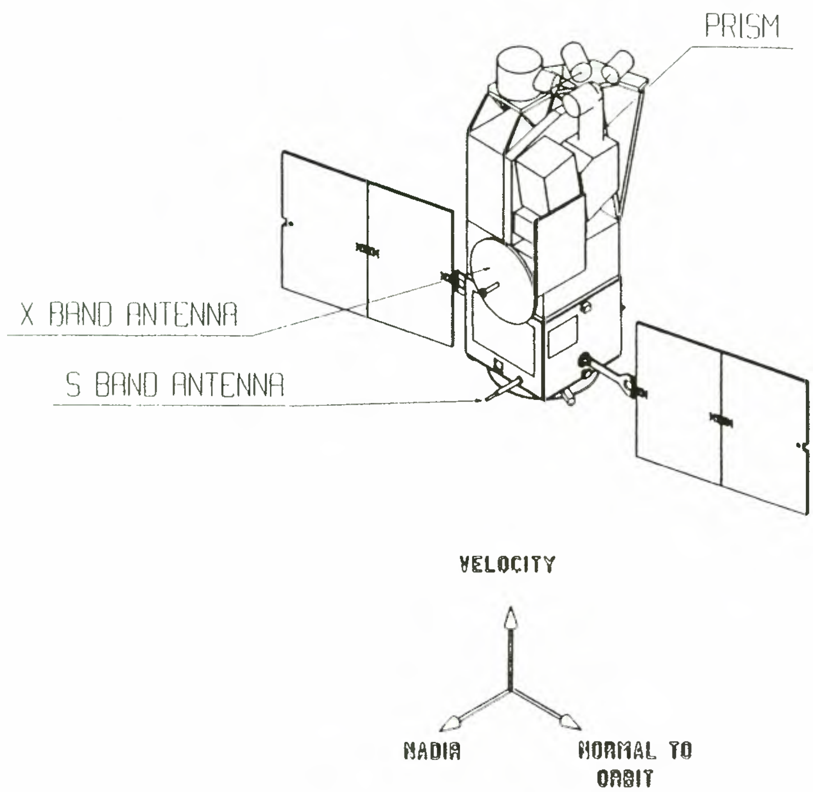

Figure 6.8. *Spacecraft configuration A*

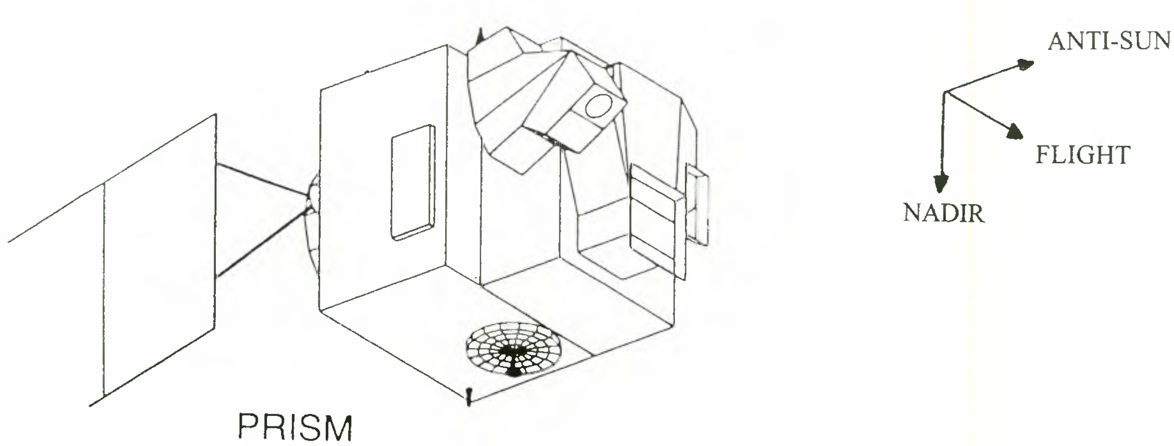

Figure 6.9. *Spacecraft configuration B*

6.4.3. Attitude and Orbit Control Subsystem (AOCS)

The satellite concept for the Surface Processes and Interaction Mission is three-axis stabilized one. The Attitude and Orbit Control System requirements are summarised in table 6.4. Orbital altitude tolerance has been set at 500 m in order to limit the drift from the selected local solar time.

Absolute Pointing Error	2.5 mrad
Absolute Attitude Determination Error	2.0 mrad
Attitude Stability	0.1 mrad/sec
Attitude Rate Determination	N.A.
Orbit Altitude Tolerance	500 m
Across-track Pointing (Roll Manoeuvre, if needed)	+/- 30 degrees max.

Table 6.4.

The AOCS requirements can be easily met using a standard AOCS architecture based on the utilization of gyroscopes, Earth and sun sensors. The possibility to use a GNSS-based attitude determination system is also being studied.

Conventional equipment will be used for AOCS actuation in the nominal pointing mode. A set of four reaction wheels with 40 Nms momentum capacity is used, and two magnetic torquers with a magnetic momentum of 140 Am^2 provide a momentum dumping capability to avoid the saturation of the wheels.

Orbit determination relies on the data from the GRAS instrument. The orbit determination requirements in support of the geolocation of the PRISM observations are very modest, since the geolocation error budget is dominated by the attitude determination accuracy and by the PRISM pointing knowledge accuracy. An orbit determination to a few metres accuracy can be obtained by limited processing of the GRAS data, which can be performed in real time within the instrument itself.

A design option to achieve the required combination of across-track and along-track pointing is to roll the satellite. At the baseline average altitude of 772 km this implies a maximum roll of 30.5 degrees. Although a detailed study of the implications of this AOCS requirement needs to be performed, it is possible to achieve a roll manoeuvre covering the whole range from -30.5 degrees to + 30.5 degrees (worst case situation) in less than two minutes. The final value for this slew manoeuvre time will depend on the actual moments of inertia of the satellite and on the settling time required to damp residual vibrations, but no fundamental problems have been identified with this scenario from the AOCS standpoint. Future studies should address this point in detail from a system point of view (e.g. thermal control aspects).

The total propellant (hydrazine) mass required to operate the mission for 6 years, i.e. 2 more than the nominal mission lifetime, has been estimated at about 40 kg. This includes all propulsion needs for orbit control (injection corrections, inclination maintenance, altitude maintenance), and is compatible with an on-board tank capacity of 50 kg.

6.4.4. Control and Data Handling, Telemetry and Telecommand

The on-board control and data handling subsystem provides all the functions for command, monitoring and control of the platform sub-systems as well as payload data acquisition and data management. It has interfaces with a number of other subsystems: the AOCS subsystem, the power subsystem, the thermal subsystem and the TM/TC subsystem. The science data from the PRISM and GRAS instruments are directly transmitted to the Solid-state Mass Memory. This is a mandatory arrangement for PRISM, which, for instance in the concept A, outputs data on 17 serial lines at a maximum rate of 45 Mb/s on 8 of these lines.

A rough estimate of the size of the on-board solid-state mass memory is based on the number of consecutive 'blind' orbits, i.e. those orbits with no contact time with the ground station, which is equal to five for Kiruna. Each daylight scene observation with PRISM will last about 7 s, corresponding to some 1.6 Gb per scene, assuming conservatively, that all spectral bands would be used. The science requirement to be able to acquire 30 images per orbit in daylight translates into an on-board storage requirement of approximately 50 Gb per orbit. The additional 30 images in eclipse require much less storage, approx. 2 Gb maximum. Assuming lossless compression of the science data by a factor 1.5, the required data storage is of approximately 35 Gbit per orbit. Therefore a mass memory capacity of approximately 180 Gbit would be needed to cover all the blind orbits. However, the orbits which are blind to Kiruna have sub-satellite points covering South East Asia and the Pacific regions. Consequently the number of images required for each of these orbits will likely be much less than 30 and the size of the on-board mass memory will be correspondingly lower. A detailed optimisation of the data storage requirements will be carried out in the course of future studies.

A further reduction in the total on-board data storage requirements could be achieved by various other mechanisms which remain to be investigated:

- band selection
- band data fusion
- lossy data compression (tailored to the PRISM hyperspectral imagery).

Several developments of solid-state mass memories are underway, which are applicable to the requirements of this mission. They are compatible with data handling architectures requiring up to several hundreds Gbit memory capacity, although at a significant cost in terms of mass, power and volume (as a rough guideline, one Gbit of additional memory implies a 0.5 kg mass and 0.5 W power consumption increase).

The TM/TC architecture is based on two main elements:

- an S-band link used for transmitting housekeeping TM and uplinking telecommands at 4 kbit/s
- an X-band link used for science data downlink at 100 Mbit/s.

The S-band link uses a low-power transmitter (2.24 GHz) and a receiver (2.07 Ghz) connected to two antennas for omnidirectional coverage, whereas the X-band link uses a high-power transmitter at about 8.4 Ghz. Both subsystems are fairly conventional and much of the equipment developed for instance in the frame of the ERS and ENVISAT programmes can be re-used. As further described in Sect. 6.5, a single high-latitude ground station is sufficient for operating both S-band and X-band links.

TM/TC modulations on the S-band link will be in accordance to ESA standards.Ranging will also be implemented according to the ESA standards, although it will only need to be used in the LEOP and as a back-up to the GNSS-based position determination in the subsequent phases.

The X-band science data downlink will basically consist of a modulator section, a power amplifier section and an antenna with the related feeding system. The science data stream will be fed from the solid-state mass memory into the modulator section, where it will be encoded and modulated on the RF carrier. An RF power of 20 W is required to transmit 100 Mbit/s, assuming Reed-Solomon encoding of the data.

6.4.5. Electric Power

The average power consumption for the payload module is approximately 350 W. The power consumption for the spacecraft subsystems should not exceed 150 W, resulting in a total satellite power consumption of approximately 500 W.

The resulting average gross power required from the solar arrays is of about 1100 W. This can be generated using a six-panel solar array (note that only four panels are shown in figure 6.8). Using GaAs cells, the total solar array area needs to be approximately 7 m^2.

The total battery capacity required is around 40 Ah. A single 40 Ah NiCd battery can be used, with a maximum depth of discharge of 40%.

6.4.6. Spacecraft Budgets

Table 6.5 provides a summary of the preliminary mass and power budgets for the mission.

	Mass (kg)	Average Power (W)
Payload Module	600	350
Platform	300	150
Propellant	50	NA
Total	**950**	**500**

Table 6.5.

6.5. Ground Segment and Data Processing

6.5.1. Constraints and Guidelines

The ground segment concept and data processing approach for the Land Surface Processes and Interaction Mission complies with the goal of maximum efficient re-utilization of the available ESA facilities, so as to reduce new investments in ground resources. The cost-effectiveness of this approach will in no way compromise the scientific return of the mission.

The primary constraints which derive from this approach can be summarized as follows:

a) the mission will rely on a single Command and Data Acquisition Station at a high-latitude location, e.g. in Kiruna (S), having a maximum downlink data rate of 100 Mb/s (present Kiruna capabilities);
b) overall user coordination, acquisition and processing of user requests, data archiving, processing up to level 1b and dissemination to the users will be carried out at the Processing and Archiving Centre, e.g. at ESRIN, exploiting to the largest possible extent the experience and infrastructure created for ongoing ESA missions;
c) the satellite shall be endowed with an appropriate level of autonomy so as to relieve the ground control from a number of routine tasks and decrease manpower costs.

6.5.2. Ground Segment

From the ground segment point of view, the main characteristics of the mission are:

- high data rate (acquisition, processing, archiving and dissemination issues);
- data acquisition at each orbit;
- single payload mission (though a new experimental payload).

A command and data acquisition element in Kiruna is suitable for this architecture under the following hypotheses:

- ~250 Mbps maximum payload data rate, reduced by a factor 1.5 by on-board lossless compression
- 100 Mbps X-band downlink
- ~180 Gbit on-board solid state mass memory.

As mentioned in Sect. 6.3.1, the total contact time for the Kiruna ground station is about 100 minutes per day, which is compatible with the overall daily data volume for a downlink data rate of 100 Mb/s.

In case significantly higher payload duty cycle or data rate would be required, this would have considerable consequences on the memory size. To mitigate this problem, two stations could be used so as to avoid or limit the number of blind orbits. In the case of Kiruna and Fairbanks (USA) being used, the memory size would be reduced to about 85 Gbit for the same payload duty cycle and data rate, though at the expense of a very substantial increase in operation and data communication costs.

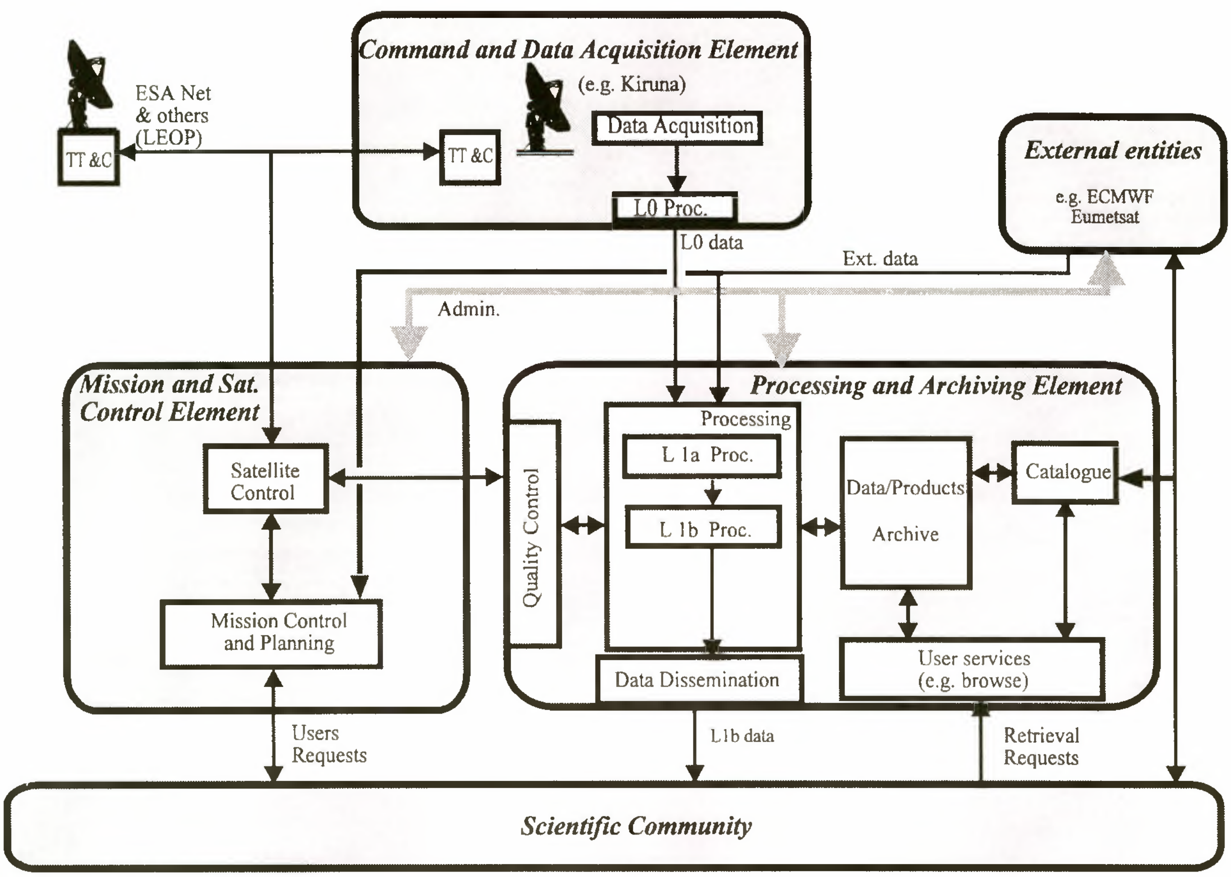

Figure 6.10. *Ground segment functional block diagram*

The ESA processing and archiving element component of the ground segment will process the raw instrument data to level 1b, which in the case of this mission will be top-of-the-atmosphere radiances which are geolocated but not resampled. It will have a single interface with the user community.

6.5.3. Mission and Satellite Control Element

For the LEOP phase, the station network will be the one used by ESA for LEO polar satellites, assuming a launch out of Kourou. Three stations are estimated to be needed for this phase. For the operational phase, the mission and satellite control centre will be in charge of the mission operations and satellite management. A high level of autonomy will be implemented in the spacecraft (> 3 days) and in the control centre. The control duty cycle in nominal conditions will be 3 days, but contact at each visible orbit will be established at each station pass and the telemetry will be automatically analysed.

6.5.4. Processing and Archiving Element

The data processing centre would receive the X-band data dump of every visible orbit from the ground station.

This centre would generate data products at level 1B and would deliver these products to the user's data processing centre(s). The delivery will take place at least within a 1 week of acquisition. The advances in technology will determine the means of dissemination.

At this stage it has to be clarified, whether it is more efficient to archive level 0 data and to process to level 1 on request from the user or to archive the data at level 1b in addition to level 0. Advances in technology and dedicated studies will determine which course to take. A browse service would be foreseen, to be used before the retrieval of a data set takes place. The requirements on the duration and type of archive retrieval services would be an important factor for the ground segment operation.

6.5.5. Available Infrastructure, Challenges

Due to the high data rate of the mission and the novelty of its payload, the reuse of existing infrastructures will be more for buildings and support services than for the data system itself. The possible sharing of the X-band acquisition chain with other parallel missions may impose undesirable requirements of synchronisation of orbits.

The main challenges for the ground segment are:

- management of a payload acquisition plan that could be variable (implications on the spacecraft operation plan, the on-board storage management and the ground data processing and archiving);
- management of a large amount of data: this implies limited operational margins for the data acquisition system, high processing power requirements for the data products generation and a powerful, fast and large archive/retrieval system.

6.6. Launcher

The mission has been designed to be compatible with the low-cost launchers for small/medium satellites, such as the Eurorockot launcher, which will be able to carry a maximum of about 1000 kg into the selected orbit when launched from Kourou and 800 kg when launched from Pletsetsk, and the LLV-2 launcher, with a load capability of 1100 kg in the orbit selected for this mission. In addition, the satellite design is compatible with medium-cost launchers, such as the Delta II 6925, which has a load capability of 2300 kg in the selected orbit.

7. Programmatics

7.1. General

The Earth Explorer Land-Surface Processes and Interactions Mission would be implemented in the frame of the ESA Earth Explorer Programme of research missions if selected after phase A studies carried out within the framework of the Agency's Earth Observation Preparatory Programme.

7.2. Critical Areas and Open Issues

PRISM is a complex instrument with challenging developments required in the areas of detectors and processing. It benefits however from technology developments for precursor concept instruments as HRIS and HRTIR and from MERIS. The development of detectors is ongoing.

The developments of solid state mass memory recorders will help to simplify largely the data handling part. Previous experience with these recorders was limited to small recorders used in scientific missions. Recent developments in the areas of memory components allow to baseline recorders of capacities beyond the 100 Gb to be baselined.

At platform level no critical issues have been identified. The use of the platform manoeuvring capability to perform across track pointing to access the target sites should not present any major challenge.

The ground segment will be demanding as expected for an instrument with the data rate and productivity of PRISM but this will not be a new issue for Europe. The development of models and assimilation methods to translate the wealth of information collected by PRISM to the GCMs will require considerable preparatory effort.

To sum up, the Land-Surface Processes and Interactions Mission could be ready for a launch in the first years of the next decade.

7.3. Related Missions and Timeliness

There are numerous missions in the area of surface processes observations. For its direct relevance one should mention ENVISAT with the SAR, MERIS and AATSR and the SPOT series and outside Europe the Radarsat and the EOS AM and PM. The NASDA planned ALOS series should provide from 2002 continuous complementary SAR and optical observations.

The LSIPM should be implemented as soon as possible in the first years of the next decade.In the current efforts to advance from understanding to prediction of climate and environment changes, Global Circulation Models are indispensable. The LSIPM is foreseen as an essential element for the establishment of such models. The contribution to and benefit from the GTOS effort is another reason to strengthen the timeliness of the LSIPM.

The anticipated potential of this mission for land-surface processes also suggests an early implementation to confirm the expectations.

7.4. International Cooperation

A major aim of this mission is to advance our understanding and ability to predict land-surface processes and their interaction with the atmosphere. This is clearly a task of global dimension with numerous initiatives worldwide. There is clearly ground for cooperation which in practical terms may have many implementation possibilities, including for instance the coordination of related missions, the mutual provision of data, the joint establishment of target sites, etc. More direct cooperation possibilities could be the joint implementation of the Earth Explorer Land-Surface Processes and Interactions Mission proper with international partners with contributions to be discussed. The cooperation options will be explored as part of the phase A studies.

7.5. Enhancements of European Capabilities

The understanding and prediction capabilities that will be developed in the framework of this mission are of high value. The observational capabilities developed for it will have considerable spin-offs in operational and possibly commercial undertakings. The development of an agile platform to allow access to the targeted sites will be an industrial asset with interest for future scientific and application missions. The LSIPM is a stand alone, research mission, but its results will support the definition of Earth Watch type of missions in the area of Land processes.

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List of Acronyms

AATSR	Advanced Along-Track Scanning Radiometer
ADEOS	ADvanced Earth Observation Satellite
ALOS	Advanced Land Observing Satellite
AOCS	Attitude and Orbit Control Subsystem
ATSR	Along-Track Scanning Radiometer
ASAR	Advanced Synthetic Aperture Radar
ASAS	Advanced Solid State Array Spectroradiometer
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVHRR	Advanced Very High Resolution Radiometer
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
BAHC	Biospheric Aspects of the Hydrological Cycle
BRDF	Bi-directional Reflectance Distribution Function
CCD	Charged Couple Device
EOS	Earth Observing System
ERS	European Remote Sensing Satellite
ESRIN	European Space Research Institute
FIFE	First ISLSCP (q.v.) Field Experiment
GAIM	Global Analysis, Interpretation and Modelling
GCM	General Circulation Model
GCTE	Global Change and Terrestrial Ecosystems
GEWEX	Global Energy and Water cycle Experiment
GNSS	Global Navigation Satellite System
GRAS	GNSS Receiver for Atmospheric Sounding
GTOS	Global Terrestrial Observing System
HAPEX	Hydrologic Atmospheric Pilot Experiment
HRIS	High Resolution Imaging Spectrometer
HRTIR	High Resolution Thermal Infrared Radiometer
IGAC	International Global Atmosphere Chemistry
IGBP	International Geosphere-Biosphere Programme
IPCC	Intergovernmental Panel on Climate Change
JGOFS	Joint Global Ocean Flux Study
JSC	Joint Scientific Committee (WCRP)
ISCCP	International Satellite Cloud Climatology Project
LAD	Leaf Angle Distribution
LAI	Leaf Area Index
LEOP	Launch and Early Orbit Phase
LLV	Lockheed Light Vehicle
LOICZ	Land - Ocean Interactions in the Coastal Zone
LSM	Land Surface Models
LSPIM	Land Surface Processes and Interactions Mission

LST	Land Surface Temperature
LTDN	Local Time at Descending Node
LUCC	Land-Use Cover Change
MCT	Mercury Cadmium Telluride
MERIS	Medium Resolution Imaging Spectrometer
MISR	Multi-angle Imaging Spectro-Radiometer
MODIS	MODerate Resolution Imaging Spectrometer
MSG	Meteosat Second Generation
NASDA	National Space Development Agency of Japan
NWP	Numerical Weather Prediction
PAR	Photosynthetically Active Radiation
POLDER	POLarization and Directionality of the Earth's Reflectances
PRISM	Processes Research by an Imaging Space Mission
PSF	Point Spread Function
SAR	Synthetic Aperture Radar
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SNR	Signal to Noise Ratio
SPOT	Systeme Probatoire d'Observation de la Terre
SVAT	Soil Vegetation Atmosphere Transfer
SWIR	Shortwave Infrared
TIR	Thermal Infra-red
TM/TC	Tele-Metry/Tele-Command
TOA	Top Of Atmosphere
VNIR	Visible/Near Infra-red
WCOS	World Climate Observing Sysytem
WCP	World Climate Programme
WCRP	World Climate Research Programme

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