SP-1196 (3)

REPORTS FOR ASSESSMENT

THE NINE CANDIDATE EARTH EXPLORER MISSIONS

Earth Radiation Mission

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THE NINE CANDIDATE EARTH EXPLORER MISSIONS

Earth Radiation Mission

ESA SP-1196 (3) – The Nine Candidate Earth Explorer Missions –
EARTH RADIATION 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 Earth observation application areas. The responsibility for this type of mission would eventually be transferred to operational (European) entities and 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 Radiation Earth Explorer Mission. It has been prepared by one of the nine Mission Working Groups that have been established to produce these Reports. The four (external non-ESA) members of this particular Mission Working Group are John Harries (Imperial College, London, United Kingdom), Jens Bösenberg (Max-Planck Institut für Meteorologie, Hamburg, Germany), Dominique Crommelynck (Institut Royal Météorologique de Belgique, Brussels, Belgium), and Robert Kandel (Laboratoire de Météorologie Dynamique, Palaiseau, France). 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.

The major thrust for this mission arises from the urgent need to better understand climate variability and change, and thus the radiative processes that play a key role in climate. The range of uncertainties in model predictions of climate change need to be reduced, in particular in the response to the observed anthropogenic changes in atmospheric composition. There are possible indications of global warming in the patterns of rising tropospheric and surface temperatures and receding glaciers and sea ice concentration and extent in the Arctic, but these observed, fairly short-term trends do not in themselves allow a prediction of the climate of the next century. A key to prediction of climate response to an increasing perturbation of the radiation balance by anthropogenic emissions is a full understanding of the role of radiation in maintaining the present climate and in governing the amplitude and evolution of large-scale climate anomalies.

All the Reports for Assessment follow a common general structure comprising seven chapters. They each start by addressing the scientific justification for particular mission and move on to detail the specific objectives. This is followed by a detailing of the specification of observation requirements and a listing of the various mission elements required 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 Issues

2.1. Background

The understanding of how the Earth's climate system operates, and how it might change state in the future, is one of the most challenging, difficult, but exciting areas of scientific endeavour known to man. Indeed, the subject could justifiably be included in any list of science's 'Grand Challenges' when entering the new millennium. At the very heart of the climate problem is the understanding of how the radiative energy balance of the planet is maintained, and how it might evolve in response to natural or anthropogenic causes. The Earth Explorer Earth Radiation Mission offers Europe the opportunity to make a quite unique contribution to advancing the understanding of the processes that control this energy balance.

Understanding of radiative processes, at the heart of the climate problem, remains inadequate for confidently forecasting changes, using large scale coupled (atmosphere-ocean) general circulation models. The processes involved include the transfer, absorption and emission of radiative energy, beginning with the incoming (shortwave, SW) solar radiation, the absorption of this radiation by clouds, the atmosphere and the surface, and then the many thermal (longwave, LW) radiation processes which result in cooling of the planet to space, in order to maintain equilibrium with the incoming solar energy.

Any changes to this balance, for example due to increases in greenhouse gases or atmospheric aerosols, can be amplified or reduced by powerful feedback processes, such as those involving water vapour and clouds: however, these remain very uncertain; the shortwave absorption properties of clouds are in doubt (Cess et al. 1995, Li et al. 1995); but whether unknown absorbers or three-dimensional cloud structure effects are involved remains an open question. The longwave emission processes involving water vapour (Sinha and Harries, 1995) and clouds (especially cirrus and marine stratus – King, 1993) are evidently important, but are not well understood. At present it is widely recognised that the radiation-cloud interaction is perhaps the largest and most serious of these problems (Hobbs, 1993). To improve the understanding of these processes, accurate and comprehensive global observations of the radiative energy entering, leaving and passing through the system (together with observation of the vertical structure of the atmosphere in cloudy as well as clear areas) need to be made.

Global observations require the use of orbiting spacecraft. The observations must be accurate, as small fractional trends in radiative energy are looked for in seeking a fingerprint of global warming. They must also be capable of picking up processes on quite small scales, so quite a high spatial resolution is required. In addition, and most problematic, they must be capable of determining the quantitative value of parameters not only as a 2-dimensional horizontal problem, but in 3 spatial dimensions, since the vertical, as well as the horizontal, distribution of radiative heating and cooling within the atmosphere is crucial.

2.1.1. The Climate System

The climate system is one of great complexity (Schneider, 1992). It includes the physical conditions prevailing at the Earth's surface, in the atmosphere, oceans, and cryosphere, on spatial scales ranging from local ('micro-climates') to global, and on time scales ranging from hours to days to millennia (Peixoto and Oort, 1992). The balance of processes taking place over these various scales determine the conditions for the existence of life and in particular the distribution of different fauna and flora over the Earth's surface. Man's habitat and economic activities depend critically on this balance.

Figure 2.1 illustrates this complexity. It must also be remembered that the natural climate system depends on its astronomical environment, and so includes the variability of radiation from the Sun due to solar cycle and orbital effects. It also depends on internal Earth processes (volcanic activity, isostasy, continental drift) operating over a very wide range of time scales.

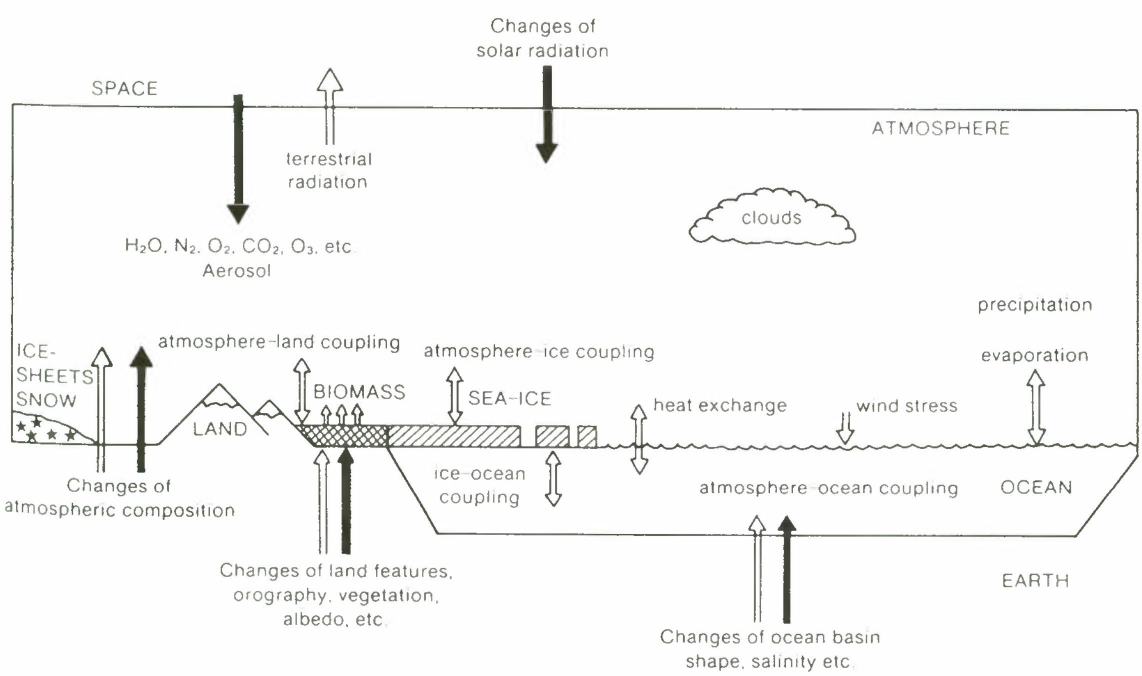

Figure 2.1. *Schematic illustration of the components of the coupled atmosphere-ocean-ice-land climatic system. The full arrows are examples of external processes, and the open arrows are examples of internal processes in climatic change (from Houghton, 1984).*

The climate system may be viewed as having at least two basic functions. The first is the 'processing' of radiation received from the Sun, by absorption of part of the incoming radiation flux of energy, the geographic redistribution of this energy in the general circulation of the atmosphere and oceans, and the re-emission to space in the form of thermal longwave radiation. In this way, equilibrium must be maintained by the planet between the incoming energy and the energy lost to space: any variations in the incoming energy, whether due to fluctuations in the solar flux, or in the amount of solar radiation absorbed by the planet must, eventually, be balanced by a change in the energy lost to space.

The second function is the operation of the hydrological cycle, which in particular supplies water to the continents and so makes life possible on land. These two functions are intimately coupled, both at the surface and in the atmosphere. Evaporation from water surfaces depends strongly on the surface radiation budget as well as on wind; the albedo of the Earth's surface over both sea and land is strongly affected by snow/ice cover. The land surface albedo depends also on the presence of vegetation, itself dependent on water availability. Longwave emission by the land surface depends on the extent to which evapotranspiration moderates diurnal temperatures. In the atmosphere, both shortwave and longwave radiation fluxes depend strongly on clouds, on their distribution in space and time, and on their macroscopic and microphysical properties, in particular on their liquid and ice water content. The radiation budget energy source and sink terms in the atmosphere and at the surface, strongly dependent on conversion to and release of latent heat, constitute the major driver of atmospheric dynamics. Some of these aspects of the radiative energy balance, and links with the hydrological cycle, are illustrated in figure 2.2.

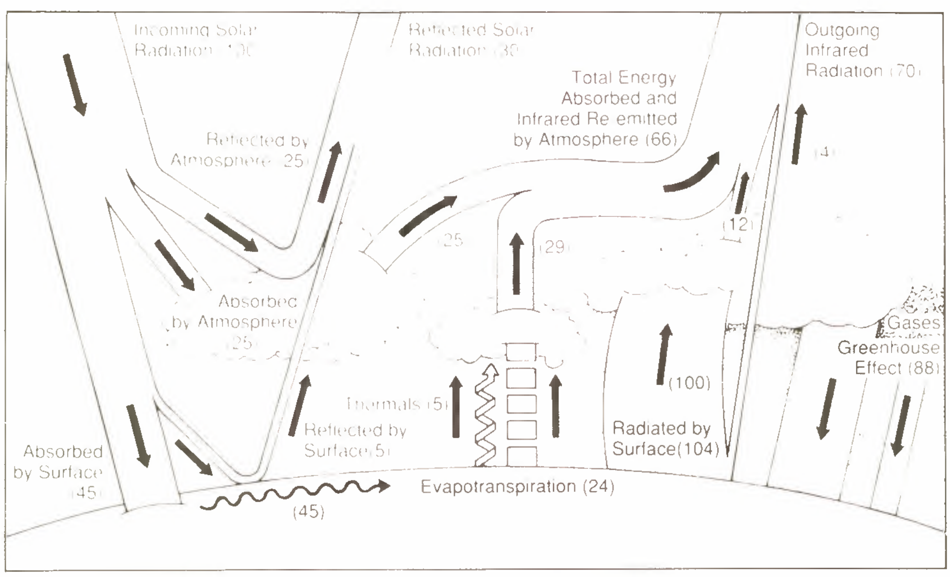

Figure 2.2. *Illustrating the interaction of radiation with the hydrological cycle. The numbers in brackets represent energy as a percentage of the average value of the solar constant (about 340 Wm-2). About 70% of the incoming solar energy enters the Earth system, the remaining 30% being directly reflected back to space.*

The aim of climate research is to understand what determines the existing state of climate (including its variability), as well as its sensitivity and response to changing natural and anthropogenic forcing factors (the distinctions to be made between climate forcing and feedback will be discussed in section 2.2 below). In order to assess to what extent models are capable of simulating reality, one must establish what that reality is. This requires observational determination of radiation and water fluxes in the climate system, of their variations with the diurnal and annual cycles and their variability on a wide range of time scales. The task is complicated by the fact that natural internal climate variability is not easily separated from climate response to perturbations by natural events (e.g. volcanic eruptions) and by anthropogenic effects. As a result, the existing state of climate may well be changing, and observational determination of this state requires adequate sampling of climate variability together with accurate monitoring of the trend of climate change.

It must be realised, however, that simple considerations of trends in global mean surface temperature – even if such trends have been detected (IPCC, 1996) – do not provide an accurate assessment of what the regional impacts are likely to be. Planning for the future requires credible model predictions of how climate could change in response to different scenarios of anthropogenic emissions on regional as well as global scales. A better understanding of the coupled processes of energy and water conversion and transport is central to this ability to model future climates. This requires better observation of the atmospheric phase changes of water (cloud formation and dissipation) and of cloud-radiation interactions, *as functions of depth in the atmosphere.* In particular, cloud-radiation feedback is a critical and still poorly determined factor in determining the sensitivity of climate to any perturbations. Hence the proposed Earth Explorer Earth Radiation Mission (ERM), which seeks to make a major contribution to this problem, is timely, topical, and of critical importance.

2.1.2. The Status of Earth Radiation and Cloud Observations

The proposed ERM takes full account of previous, important efforts to study the Earth's radiation balance from space. These will be briefly reviewed in this section.

Energy exchanges between the climate system and space are practically totally in the form of electromagnetic radiation: thus the overall planetary energy budget is identical with its radiation budget. Incident solar SW radiation (wavelength, $\lambda < 4\ \mu m$) is partly reflected (c.30%), the rest being absorbed, i.e. converted into energy within the system (cf. figure 2.2). In addition to the reflected SW flux, the outgoing LW radiation from the planet includes the thermal 'longwave' radiation ($\lambda > 4\ \mu m$) emitted by the Earth-atmosphere system. These various radiation fluxes[1] interact strongly with clouds, with the Earth's land, sea and ice surfaces, and with atmospheric gases and aerosols (Peixoto and Oort, 1992).

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[1] See Appendix for definitions of radiative energy units such as radiance, flux,etc

The Radiation Budget at the Top of the Atmosphere

Observation of the Earth radiation budget (ERB) components at the top of the atmosphere (TOA) is only possible on a global basis from space, and is essential for understanding the climate system energetics. Radiative transfer calculations alone cannot be relied on because all the absorption/emission mechanisms in the atmosphere are still not fully understood. There are large gaps in the knowledge of the three dimensional structure of cloud fields and of their radiative properties.

Early rocket measurements began in the late 1940s (Hunt et al., 1986), and since 1978 satellite measurements have become more and more precise, currently capable of detecting variations of 0.02% in the solar constant (due to solar noise), 0.2% due to solar spots and about 0.1% over the solar cycle, with an absolute accuracy near to 0.1% (see e.g. Crommelynck et al., 1995). It has been conventional to determine the spectrally-integrated (broad-band) SW and LW fluxes, without attempting the much more difficult task of spectrally resolving these fluxes. The major difficulties in obtaining absolutely calibrated broad-band SW and LW measurements from space have been progressively overcome (House et al., 1986), essentially by combining broad-band unfiltered (total channel) measurements with SW data obtained using, for example, a spectral filter to isolate radiation at LW. This is the technique used in NASA's Earth Radiation Budget Experiment (ERBE – Harrison et al., 1988), the Scanner for Radiation Budget (ScaRaB) project (Kandel et al., 1994), and adopted for the CERES (Clouds and the Earth's Radiant Energy System, NASA, 1995) and the GERB (Geostationary Earth Radiation Budget experiment: Harries et al., 1996). Accurate calibration at the level of 1% absolute accuracy or better appears attainable, using a combination of a blackbody infrared source, a calibrated lamp for the SW, and solar diffuser calibrations in flight. The spectral correction problem remains significant in the SW, although this can be reduced by incorporating simultaneous multi-channel imager data when available .

Horizontal spatial resolution of the fundamental TOA ERB measurements has been progressively improved to about 35-50 km. Because one of the important applications of ERB observation is the assessment of cloud-radiation effects, a resolution better than 100 km is certainly necessary in order to have a reasonable chance of obtaining cloud-free scenes from which the 'cloud radiative forcing' (see section 2.2.2) can be computed.

Converting radiance measurements into fluxes (irradiances) requires knowledge of the anisotropy of the radiation field (Smith et al., 1986). Individual SW flux estimates obtained using currently available angular correction models (derived from Nimbus-7 data obtained in 1978-79, cf. Suttles et al., 1988) remain subject to large errors. Although improved angular models (e.g. based on new analyses of ERBE, ScaRaB and geostationary satellite data) may reduce errors in a statistical sense, estimates of reflected shortwave fluxes will remain subject both to random and to systematic errors (the latter because of biased angular sampling). Individual pixel flux estimates can be improved, provided that the cloud cover within the pixel is determined in real time by simultaneous multi-channel imager data with high spatial resolution (better than 1 km). TOA SW and LW fluxes measured by the ERBE missions have been shown to be accurate to about +/- 5 Wm^{-2} on a global basis, but errors can have much higher values on a regional basis (e.g. Slingo and Webb, 1992).

Measurements of the spectrally integrated fluxes at the TOA are essential for studying climate system energetics, but they provide no vertical resolution of processes in the atmosphere. The emitted LW spectrum does however contain such information, which is routinely exploited in the inversion of infrared and microwave sounder data from the operational weather satellites in polar orbit (Eyre et al., 1993). Similarly, brightness temperatures observed from geostationary weather satellites in different narrow bands of the thermal infrared are often used to assign cloud heights and winds derived from cloud displacements (see e.g. ESA, 1987). More complete infrared spectra of outgoing LW radiation were obtained as early as the mid-1970s with the Infrared Interferometer Spectrometer (IRIS) on board Nimbus-4 (Kunde et al., 1974), and also with the GDR Fourier spectrometer on board Soviet Meteor satellites (Spänkuch, 1982). Figure 2.3 shows the TOA radiance measured by IRIS-D on Nimbus-4 (Hanel et al., 1971). It is not clear how much information is available in such a spectrum regarding climate trends (Goody et al., 1995).

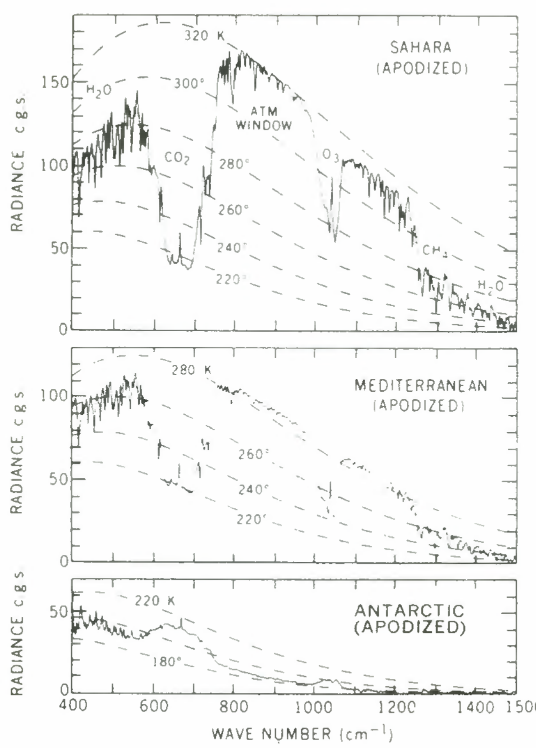

Figure 2.3. *The TOA radiances recorded by IRIS-D on Nimbus-4. The upper panel shows a desert case, the middle an intermediate case over water and the lower panel a polar case. Radiances of blackbodies at several temperatures are superimposed (after Hanel et al., 1971).*

Radiation Budget at the Surface and Within the Atmosphere

The TOA ERB is of course only a boundary quantity, which can be interpreted both as a source/sink of energy for the combined atmosphere and ocean circulation, or as an integrated signal of what is happening within the climate system. However, processes at the surface are more directly related to the surface energy budget components (radiative and non-radiative), while atmospheric processes are more closely related to the vertical flux gradients or flux divergence.

Although radiation budget measurements have been made at or near the surface of the Earth for many decades, severe problems remain both with respect to the absolute calibration of the radiometers used, and more importantly, with the many large gaps in the observing network, especially (but not only) over the oceans. Significant efforts to improve surface measurements are being made in the American ARM program (DoE, 1990). However, considering the difficulties of obtaining global coverage at the surface, another major effort is actually focussed on the use of satellite data associated with ground-based radiometric observations performed at reference sites as well as temperature, humidity profiles and cloud cover from assimilated synoptic observations to estimate the surface and atmospheric radiation budget components (Darnell et al., 1992).

The amount of energy deposited into, or extracted from the atmosphere due to diabatic radiative processes is determined by the vertical flux gradients, dF/dz, in units of Wm^{-3} (eg. see Salby, 1992). This is a difficult measurement to make, firstly because of the problems of actually introducing an accurate radiometer into the atmosphere, in an aircraft or on a balloon; and secondly because high accuracy in the upward and downward fluxes is required if the flux gradient is to be of useful accuracy. There have been some systematic campaigns of in-situ LW flux measurements over the USSR (Zaitseva, 1974). However, because of the difficulties associated with making accurate measurements, it is customary to integrate over more or less large volumes and to focus interest on the radiation fluxes (units of Wm^{-2}) passing through limiting surfaces at the top of the atmosphere and the surface. This is also challenging because the fluxes are highly dependent on the physical characteristics of the ever-changing cloud surfaces in thermodynamic interaction with their immediate surroundings.

Clouds, Water, and Aerosols

Computation of the radiative forcing associated with the increase in atmospheric carbon dioxide and other greenhouse gases over the past 50 years is relatively straightforward, but observed climate change during this period does not follow this forcing closely. Recently it has been shown that better agreement between observed and modeled climate change, at least in recent years, can be obtained when radiative forcing by anthropogenic aerosols is taken into account (IPCC, 1994). This includes both a direct component, due to reflection of sunlight by the aerosols, and an indirect component related to the enhancement of albedo of certain cloud fields when more sulphate aerosols are present. However, an aerosol climatology does not presently exist, and aerosol optical properties, as well as their efficiency as cloud condensation nuclei, are not well known.

Early work (e.g. Raschke et al., 1973) showed that the planetary albedo was close to 30%, significantly less than the 37% estimated earlier. This difference could largely be explained by cloud cover being lower than previously estimated for the tropical and subtropical zones, especially in the Southern hemisphere. There was some improvement in cloud climatology on the basis of satellite data in the following years, but a systematic effort to improve cloud climatology only began with the organization of the International Satellite Cloud Climatology Project (Rossow and Schiffer, 1991).

With systematic data collection and estimation of cloud cover and properties, ISCCP has contributed to a cloud climatology based both on surface and on satellite data, including information on variability (including the diurnal cycle). However, the ISCCP has only been collecting data since 1983, so that the sample of ENSO (El Niño-Southern Oscillation – Philander, 1990) events, occurring on average every 3-5 years, is still rather small, and the record is not long enough for trend detection. Neither is there an adequate basis for empirical estimation of cloud-radiation feedback. Also, the existing ISCCP products remain inadequate for accurate evaluation of cloud liquid water content and water phase conversion rates. A difficult aspect of this question is the known strong diurnal variation of cloud processes, which means that geostationary as well as low Earth orbit observation is necessary. The ISCCP products include only very crude cloud top height assignments, and virtually no information on overlapping multiple cloud layers. The ISCCP data are also generally inadequate for determination of cloud cover over snow or ice-covered surfaces, and for the detection of cirrus. Spectrometric data (e.g. Smith et al., 1989) could prove useful in determining the radiative influence of cirrus, which may be critical for climate sensitivity.

With regard to atmospheric water vapour, it is not absolutely certain that the present descriptions of the water vapour feedback used in models is correct: it seems likely that not only is the distribution of humidity in the upper troposphere poorly understood, but so also is the spectroscopy of the atmosphere in the far infrared, where considerable radiative cooling to space is thought to occur (Clough at al, 1992; Sinha and Harries, 1995). Global coverage using satellite passive infrared and microwave sounding data is not at present satisfactory for either the lowest or the highest layers of the troposphere. It is believed that the greenhouse effect is particularly sensitive to changes in upper-level tropospheric humidity.

2.1.3. International Context

In order to set the scene for the proposed ERM, it is useful to briefly consider two aspects, first the international scientific programmes which are in place or are planned, and which will provide a framework for the new observations to be made by ERM and, second, the planned space projects which relate to the objectives of the ERM. In summary at this point, it is clear that there exists a strong scientific framework to which ERM will contribute substantially;

and that the proposed ERM will provide a quite unique and novel mission within the framework of other programmes.

International Programmes

The International Geosphere-Biosphere Programme (IGBP) was set up in 1987, in order to gain a better understanding of the interaction between the physical-chemical processes on the one hand, and the biospheric processes on the other, that govern the climate of the Earth, and that regulate the Earth's capability to support life (IGBP, 1986). This programme has developed a number of core projects, covering topics such as atmospheric chemistry, ocean fluxes, past global change, coastal zones, biogeochemical cycles, agriculture and forestry, and others. Of particular note for ERM is the programme called GEWEX (Global Energy and Water Experiment), which has been set up in collaboration with the World Climate Research Programme. GEWEX provides a valuable framework for studies of the role of the hydrological cycle in global energetics.

The World Climate Research Programme, WCRP, itself part of the World Climate Programme, is a cooperative venture between the World Meteorological Organisation (WMO), the United Nations Environment Programme (UNEP) and the International Council of Scientific Unions (ICSU). The WCRP has provided an international umbrella for a wide range of activities concerned with the physical climate system, including the atmosphere, the oceans, the cryosphere and the land. Many scientific programmes have been generated under the auspices of the WCRP, and a large range of results have been published in a series of technical memoranda. The joint GEWEX programme with the IGBP has already been noted.

Space Programmes

The National Aeronautics and Space Administration, NASA, in the USA, has operated a number of successful projects and programmes, including, amongst many, the Nimbus series of satellites, the Earth Radiation Budget Experiment (ERBE), and currently the Upper Atmosphere Research Satellite (UARS). At present, the main thrust of NASA's programme in Earth system science is via the Mission To Planet Earth (MTPE) initiative, which includes the Earth Observation System (EOS) system of satellites. A useful summary of this programme may be found in the 1995 MTPE/EOS Reference Handbook (NASA, 1995). Of direct relevance to the ERM proposal will be the CERES instrument, which will fly in 1997 on the low-inclination Tropical Rainfall Measuring Mission (TRMM), and on the EOS AM-1 and PM-1 satellites in (about) 1999 and 2001, respectively. CERES is a successor to ERBE, and will make SW and LW measurements in a wide swath.

Europe has contributed with ERS-1, e.g. by providing highly accurate sea surface temperatures. With the present ERS-2 observations of radiatively important minor species (e.g. ozone) are provided. In coming years the ENVISAT satellite will provide a more detailed picture of those species.

The European organisation for the exploitation of operational meteorological satellites, EUMETSAT, with their present geostationary Meteosat contributes to the ISCCP by providing climatological data. In the future, MSG (Meteosat Second Generation) satellites should provide even more important data assuming that these satellites would carry both narrow-band imagers (SEVIRI, scanning enhanced visible/infrared imager) and broadband radiometers (GERB, geostationary ERB instrument). Data from geostationary satellites are of prime importance for ERM in providing observations of time dependent processes (due to their ability to monitor continuously). Another very important contribution would come from the planned series of operational polar orbiting satellites, METOP. Some of the observations from METOP will be essential for the ERM, e.g. temperature and water vapour profiles from the operational sounders.

Other programmes include the Earth observation programme of Japan. Satellites of the ADEOS series will support radiation studies providing observations of bidirectional reflection from POLDER (e.g. see NASA, 1995). TRMM, which focuses on tropical precipitation, should give some insights into the energetics of the lower latitudes. A follow-on mission (TRMM-2 or ATMOS A1) is under consideration.

The French-Russian-German ScaRaB (Kandel et al., 1994) on board the Russian Meteor-3/7 polar orbiting satellite provided data from end February 1994 to early March 1995; this is currently being analyzed by the International ScaRaB Science Working Group. Two additional ScaRaB flight models exist, and there is a possible flight opportunity on board the Russian RESSURS satellite due to be launched in April 1997. It should be noted that the CERES scanner can serve the same function as ScaRaB except that it has no narrow channel in the visible, although it does have an infrared window channel.

2.2. Scientific Issues

2.2.1. Summary

The international effort to understand the climate system is one of the most important scientific challenges of today. The climate is complex and difficult to understand, involving many interacting feedback processes. Amongst these, radiative processes lie at the very heart of the understanding of the climate system. It is the interaction of the radiative fields with the molecules of the atmosphere, with aerosols and with clouds, as well as with the surface, that determine the radiative balance. This balance may be disturbed by mankind's impact, or by natural changes, in many different ways of which the understanding is still limited. Presently there is a range of climate fluctuations, including those due to global warming, desertification, ozone depletion and El Niño, causing potential changes to UV radiation, fresh water supply, rainfall, sea ice extent and iceberg distributions, and other phenomena. It is a top priority to understand these processes.

Such an understanding will depend on two things: first, the development of comprehensive and powerful computer models of the climate; and, second, the capability to make accurate, global observations by which processes can be understood, and with which the models can be tested.

2.2.2. Forcing and Feedback in Climate

Both external and internal factors affect climate. External factors are those that affect the climate system, without being affected by it; the solar irradiance, spectrum and activity must all be included amongst these. The same is true of the parameters of the Earth's orbit, less so of the Earth's rotation, which can indeed depend slightly on the modification of the Earth's moment of inertia, e.g. when water accumulates as ice around the poles. The input of volcanic aerosol due to eruptions is another parameter counted as external. Among the internal factors, certainly the planetary albedo must be included as well as the greenhouse effects of atmospheric absorbing gases, aerosols and clouds. The plant cover of land surfaces is evidently sensitive to climate, and deforestation and other land use changes by man can have impacts on climate.

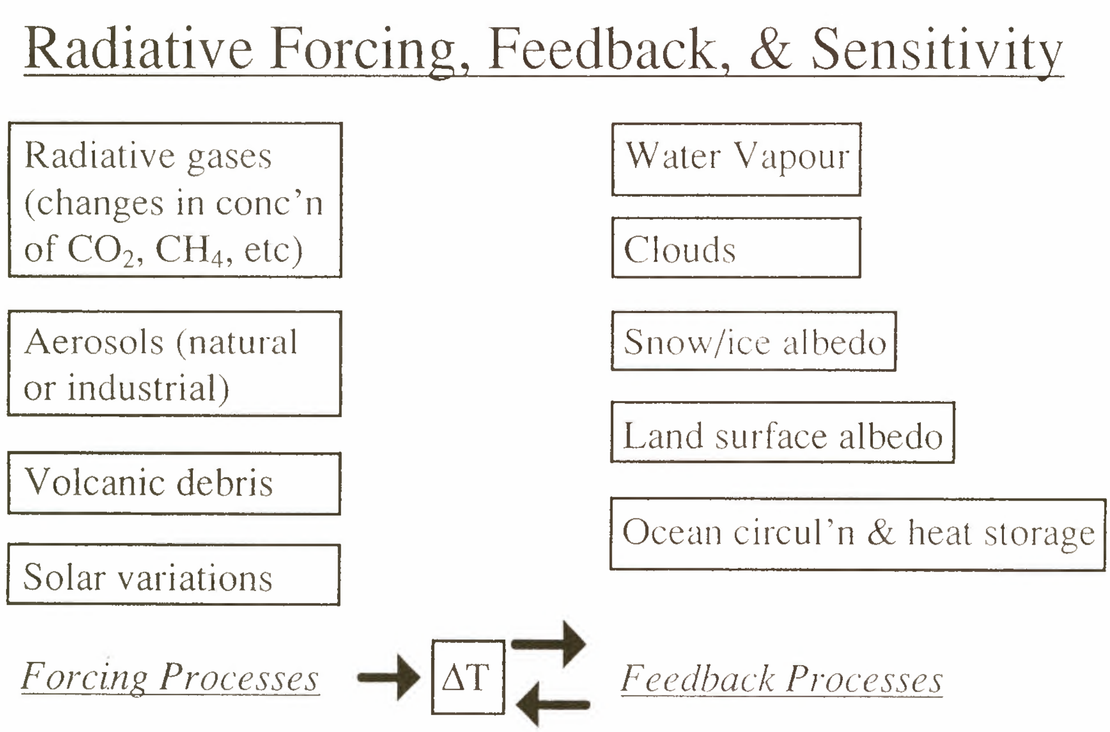

Figure 2.4. *Illustrating how forcing processes (change in gas concentrations, etc.) cause changes in surface temperature (T), which can then be amplified or decreased by feedback processes (water vapour, etc.).*

The concepts of forcing and feedback have been developed by climate researchers using an analogy with the systems often used by engineers. Consider a state of equilibrium of a system. A forcing is any perturbation of this state. The response of the system (or of sub-systems of it) may be to positively amplify the perturbation (positive feedback), or to negatively dampen the forcing (negative feedback). Positive feedback implies instability of the equilibrium state, because the response drives the system farther away from equilibrium. On the contrary, negative feedback drives the perturbed system back toward the equilibrium state, ensuring stability. Figure 2.4 illustrates in schematic form the interplay between forcing and feedback (see e.g. Raval and Ramanathan, 1989).

The Earth radiation budget, ERB, may be defined as the net energy flux at the top of the atmosphere (TOA) per unit area in a column of air, and is given by:

$$R = Q^{\downarrow} - F^{\uparrow}, \tag{2.1}$$

where $Q^{\downarrow}$ is the downward flux of energy from the Sun at the TOA, and $F^{\uparrow}$ is the upward flux of terrestrial radiation, also at the TOA. If A is the planetary albedo, and F_S is the solar constant (solar flux arriving at the Earth), then for a spherical, rotating Earth, the following relationships hold (Houghton, 1991)

$$R = Q^{\downarrow} - F^{\uparrow} = (1-A)\frac{F_S}{4} - F^{\uparrow} \tag{2.2}$$

$$= (1-A)\frac{F_S}{4} - \varepsilon\sigma T^4 \tag{2.3}$$

where ε = emissivity of the Earth, σ = Stefan-Boltzmann's constant and T the surface temperature. For equilibrium, the radiation balance R must be zero, linking T with F_S and A in equation (2.3). If there was a perturbation (e.g. of albedo A) affecting the energy input to the planet, then if only T was allowed to change in response, it follows:

$$\Delta R = 0 = \Delta Q^{\downarrow} - 4\,\varepsilon\sigma T^3\,\Delta T \tag{2.4}$$

the change in temperature can be obtained

$$\Delta T = \frac{\Delta Q^{\downarrow}}{(4\,\varepsilon\sigma T^3)} = \frac{(\Delta A\,\frac{F_S}{4})}{(4\,\varepsilon\sigma T^3)} \tag{2.5}$$

Equations (2.2) to (2.5) illustrate several things: first, the importance of the global albedo to the surface temperature and, second, that radiative cooling to space (the second term on the right hand term of equation (2.4)) is a strong negative feedback to any perturbation of the radiation balance, for example caused by carbon dioxide increases. The former point illustrates the great importance of a complete understanding of the radiative effects of clouds, since the albedo is largely dictated by cloud distributions.

For a stable climate system, presumed to exist near an equilibrium state, the observed stability over the last ten thousand years implies that negative feedbacks, including the one just described, are able to balance all positive ones, such as the water vapour greenhouse feedback. This is almost certainly due to the strong negative feedback represented by increase of infrared cooling to space as temperature rises. Strictly speaking, only changes in factors purely external to the climate system (such as the solar irradiance, Earth's orbital parameters, and volcanic activity) should be considered as forcing factors of climate change. The rapid anthropogenically-caused rise in the concentrations of certain aerosols and greenhouse gases can however be considered among these. On the contrary, clouds should be considered to be part of the feedback process.

There is clearly room for uncertainty as to whether a particular process should be classified as a forcing or a feedback, and indeed, there has been some confusion on this point in the literature. When using a model of the climate system some factors can be treated as either. An example is the case of the so-called cloud radiative forcing (CRF), used to describe the effect of cloud on the TOA radiative fluxes. The process is, really, a feedback, since the cloud changes are a response to other forcings, but the idea of the CRF is well entrenched in the literature (eg. Charlock & Ramanathan 1985, Ramanathan et al., 1989). It is useful to summarise what is meant precisely by CRF.

The CRF is the difference between the TOA energy budget (ie net flux, $Q^{\downarrow} - F^{\uparrow}$) for a given column under clear and cloudy situations:

$$CRF = R - R_{clear} = (Q^{\downarrow} - F^{\uparrow}) - (Q^{\downarrow}_{clear} - F^{\uparrow}_{clear}) = (Q^{\downarrow} - Q^{\downarrow}_{clear}) + (F^{\uparrow}_{clear} - F^{\uparrow}) \quad (2.6)$$

$$= C_{SW} + C_{LW}, \quad (2.7)$$

where, as above, R is net radiation, $Q^{\downarrow}$ is the downward solar flux, $F^{\uparrow}$ is the upward thermal flux (both for cloudy skies), and $Q^{\downarrow}_{clear}$ and $F^{\uparrow}_{clear}$ are the clear sky equivalents. As shown, it is possible to separate the effects of CRF into SW and LW parameters, C_{SW} and C_{LW}. With increasing cloud, C_{SW} is negative and C_{LW} is positive, since increased cloud causes more reflection to space of solar radiation, yet more trapping of thermal radiation seeking to escape to space. Some examples of measurements of C_{SW} and C_{LW} are shown in figures 2.5a to 2.5c, from the ERBE experiment (Hartmann, 1993). In figure 2.5a, where C_{LW} is shown, maximum values of the LW cloud forcing of order 40 Wm^{-2} are seen above centres of high convective clouds in the sub-tropical belts. In figure 2.5b, values of C_{SW} reach as high as -120 Wm^{-2} over the cloudy, sub-polar zones of the summer hemisphere. The zonal average values of both LW and SW, and of net radiation are shown in figure 2.5c for the annual average. Current best estimates of the globally averaged net cloud forcing is about -20 Wm^{-2}.

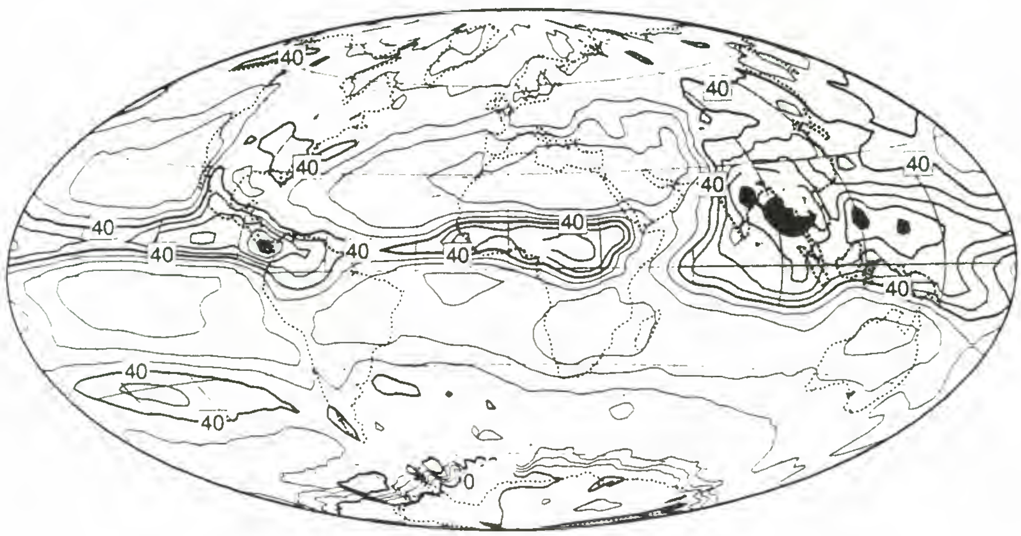

Figure 2.5a. *Longwave cloud forcing, C_{LW}, determined from two years of ERBE data (1985-87), in units of Wm^{-2}, for June-August: Values greater than + 40 Wm^{-2} are lightly shaded, and greater than + 80 Wm^{-2} are heavily shaded (after Hartmann, 1993).*

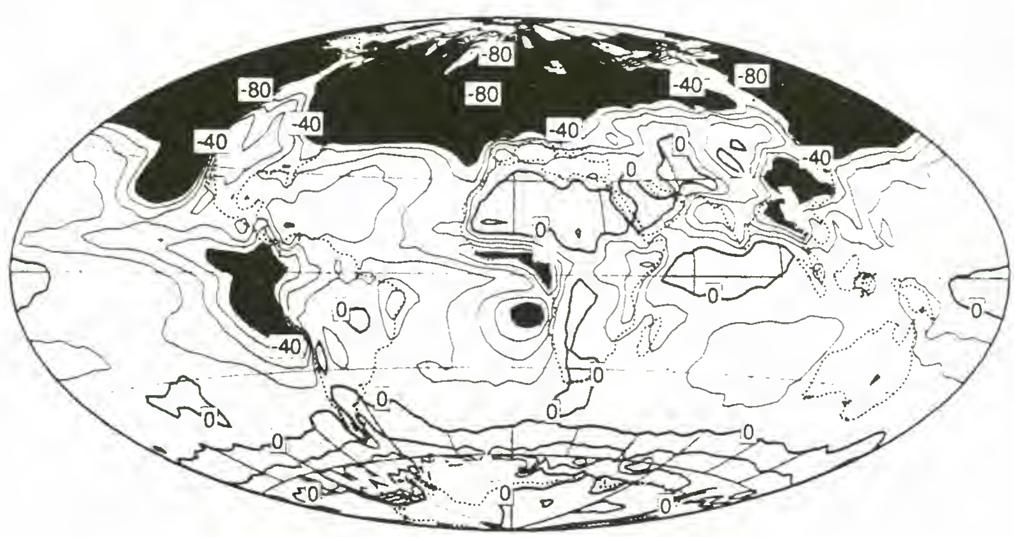

Figure 2.5b. *As **(a)**, except shortwave cloud forcing (C_{SW}). Values more negative than - 40 Wm^{-2} are lightly shaded, and more negative than - 80 Wm^{-2} are heavily shaded) (after Hartmann, 1993).*

The TOA CRF may be derived either from model output, or from measurements (eg based on ERBE or ISCCP data). In either case, the derived CRF integrates over the effects of clouds at different levels. An important factor is diurnal variation, because SW CRF depends on the incident solar irradiance. Another major factor is the distribution of clouds with altitude, with the maximum contributions to the LW CRF at TOA coming from optically thick high-level clouds, because these emit most strongly to space, at the lowest temperature. Information on the vertical distribution of clouds and radiative fluxes is therefore of the highest importance, but is largely unavailable now. This will be a principal target of the proposed ERM.

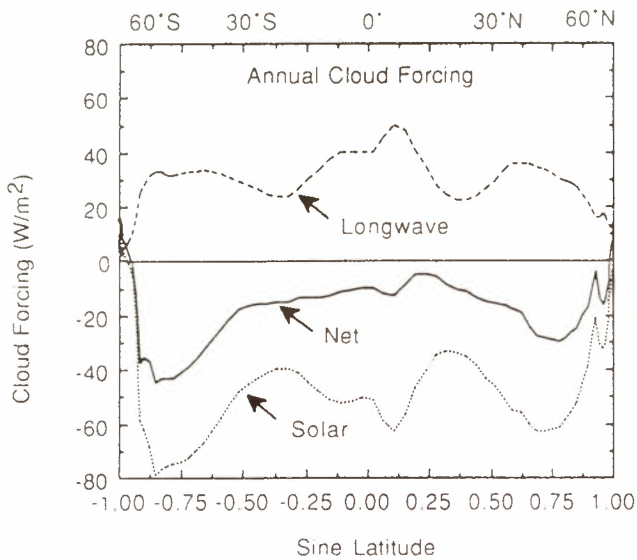

Figure 2.5c. *Zonal and annual averages of cloud forcing of longwave, solar, and net radiative fluxes. The quantities are plotted as functions of the sine of the latitude. Thus, the areas between the curves and the zero line are proportional to the contribution of each latitude to a global area average (after Hartmann, 1993).*

Similar definitions for a forcing parameter, divided between LW and SW effects can be derived for aerosols in the atmosphere. In this case, it is the SW cooling (reflection) effect of aerosols which is thought to be of the greatest importance. Calculations of the radiative cooling effect of typical aerosols have been carried out, e.g. by Charlson et al. (1992), and an example of the effect is shown in figure 2.6, where, not surprisingly, the albedo effect is localised regionally over the areas of industrial aerosol production. This localisation means that, despite operating in the opposite sense to greenhouse gas warming, this effect cannot be invoked as a counter to the latter: the quite different regional distributions of warming and cooling will, if anything, lead to increased climatic destabilisation.

It is recognised (IPCC, 1994, 1996; King, 1993; Hartmann, 1993; Senior and Mitchell, 1993) that climate-cloud-radiation feedback is the major source of uncertainty in predicting climate sensitivity to the radiative forcing of increased greenhouse gas abundances. However, while for the feedback effect due to water vapour a wide consensus exists that greenhouse warming will lead to increased absolute humidity, amplifying the greenhouse effect of water vapour (the positive water-vapour feedback), there is considerable disagreement and uncertainty regarding the effect of cloud feedback, for several reasons. First, the effects depend strongly on the type of cloud: low water clouds have a small infrared greenhouse effect, since they are at a temperature close to that of the surface; but they usually have a high visible reflectivity, and so cool efficiently. High cirrus clouds often only have a small albedo effect, because they are optically thin in the visible, but they can have significant emissivity in the infrared, and so are efficient greenhouse traps for outgoing LW radiation. Note however that it has also been suggested that when extensive thick cirrus fields develop in tropical regions, the albedo effect ultimately dominates and introduces a strong negative feedback (Ramanathan and Collins, 1991), although this is highly controversial. Secondly, the detailed radiative effects of clouds (especially cirrus) can depend strongly on the microphysical properties of the cloud, which are difficult to determine. And, thirdly, clouds move and change shape, in all three dimensions, which provides an added degree of uncertainty of their effect on the climate.

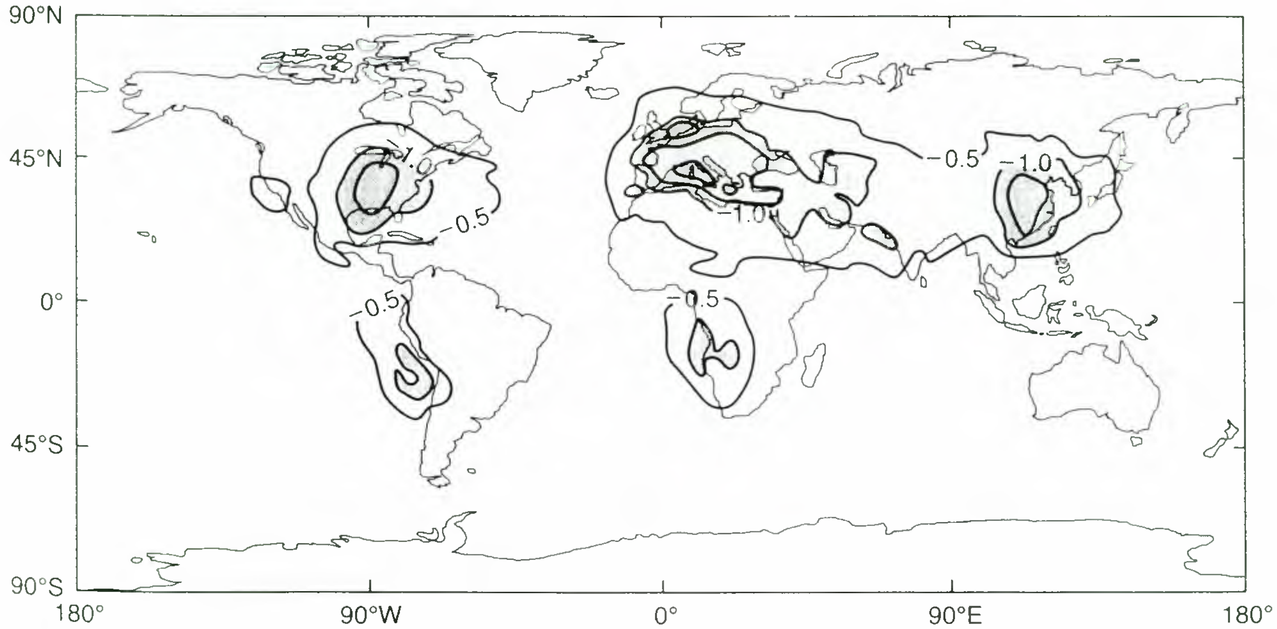

Figure 2.6. *Modelled distribution of annual mean radiative forcing due to anthropogenic sulphate aerosols, in units of Wm-2 (from Charlson et al., 1992).*

Table 2.1 illustrates some of the variation associated with assessing the cloud forcing, taken from a study by Hartmann (1993). In this study, ERBE data have been analysed, to provide the radiative effects of five cloud types, based on the classifications developed by ISCCP. The table shows the seasonal, area-averaged values of cloud cover fraction, C_i , and albedo, A, (both in %), the outgoing LW radiation (OLR) and net radiation (both in Wm^{-2}), plus the parameters ΔOLR, ΔA and ΔNet, indicating the ratio of OLR, A or Net, normalised by the globally averaged cloud amount for that type of cloud. The strong infrared warming (positive values) effect of high clouds is clear, as is the strong forcing of the albedo by thick high and mid-level clouds. Quite clearly, the true situation in any given case depends strongly on the actual vertical distribution of cloud, as well as its horizontal distribution.

	Type 1: High, thin cloud		Type 2: High, thick cloud		Type 3: Mid, thin cloud		Type 4: Mid, thick cloud		Type 5: low cloud		Sums of averages
Parame-ters	JJA	DJF	JJA	DJF	JJA	DJF	JJA	DJF	JJA	DJF	
C_i	10.2	10.0	8.5	8.8	10.7	10.7	6.5	8.2	27.2	25.9	63.3
OLR	6.5	6.3	8.4	8.8	4.8	4.9	2.4	2.4	3.5	3.5	25.8
A	1.2	1.1	4.1	4.2	1.1	1.0	2.7	3.0	5.8	5.6	14.9
Net	2.4	2.3	-6.4	-7.5	1.4	0.8	-6.6	-8.5	-15.1	-18.2	-27.6
ΔOLR	63.7	63.0	98.8	100	44.9	45.8	36.9	29.3	12.9	13.5	40.8
ΔA	11.8	11.0	48.2	47.7	10.3	9.3	41.5	36.6	21.3	21.6	23.5
ΔNet	23.5	23.0	-75.3	-85.2	13.1	7.5	-102	-104	-55.5	-70.3	-43.6

Table 2.1. *Global area-averaged cloud forcing by type of cloud (JJA = June/July/August, DJF = December/January/February),* C_i *= cloud cover fraction [%], A = albedo [%], OLR = outgoing LW radiation [Wm-2], Net = net radiation [Wm-2],* $\Delta X = X/C_i \times 100$ *[%] where X = OLR, A or Net (after Hartmann, 1993).*

2.2.3. The 3-dimensional Distribution of Heating

A major problem in the use of space data in the past has been the fact that only TOA radiances, and fluxes, may be obtained from satellite sensors. Passive sensors are able, through now well-established techniques of remote sounding (e.g. Harries, 1995), to interpret the wavelength dependence of upwelling radiance in terms of the vertical distribution of temperature and absorbing gas density, but only with quite low spatial resolution (of order 1 scale height, or 6-8 km). Moreover, most sensors are able to do this only in cloud-free areas.

In the case of cloudy, or partly cloudy skies, the vertical distribution of clouds strongly affects the distribution of radiative heating or cooling in the atmosphere, through the vertical flux gradient, dF/dz. It is only, through the use of active sensors, radar and lidar in particular, possible to extract any information about the vertical distribution of cloud, and hence to infer the heating rates.

To illustrate the importance of vertically resolved information on clouds and related radiatively important phenomena in the atmosphere some examples are given below.

Cirrus

Thin cirrus clouds, even with an optical depth as low as 0.1 can cause more than a 10 Wm^{-2} change in the downwelling longwave radiation. Thus, cirrus clouds are believed to play a major role in the cloud feedback mechanism controlling part of the climate system, in particular through the anvils of deep convection systems in the tropics. But the strength of this feedback, and maybe even the sign, depends on the actual height and optical depth of these clouds. Therefore it is particularly important to detect these clouds and make a proper height assignment. However, thin cirrus, especially when over land or over other cloud layers, cannot be detected reliably by passive sensors. The reason for this is that the signature of these clouds in the radiation field is ambiguous, since changes in brightness temperature can be attributed to either changes in cloud cover or changes in albedo of the lower layers. A combination of lidar and radar can provide the necessary information about altitude and optical depth of cirrus layers.

Marine Stratus

Another important atmospheric feature which has to be addressed is the formation of extended marine stratus cloud decks over the eastern subtropical oceans. These clouds cover large areas and play a significant role in determining the surface radiation budget. The net cloud forcing is approximately 100 Wm^{-2} for complete cloud cover. A reasonable goal for the accuracy required to study this radiation field would be about 5 Wm^{-2}, for monthly averages, which implies determination of the fractional cloud coverage to about 5% accuracy. This requires precise cloud detection during the full diurnal cycle, at nighttime as well as during the day. With present technology, however, marine stratus is hard to detect during nighttime, because its brightness temperature is close to that of the sea surface. The combination of radar and lidar measurements proposed for ERM will serve to detect both upper and lower boundaries of the majority of these clouds, and hence help to assess the impact of marine stratus on both the global circulation and the regional weather systems.

Aerosol Layers

Under clear sky conditions, boundary layer aerosol can change the net radiation flux at the surface to between 10 Wm^{-2} and 50 Wm^{-2} depending on the aerosol loading. There is generally a lack of information on the global aerosol distribution. Lidar observations can aid in the detection of those events which have a strong influence on the radiation budget.

Vertical and Horizontal Cloud Structure

This example illustrates a more general problem. It is obvious that the determination of fractional cloud cover is extremely important for the radiation budget. Consequently rather stringent requirements have been set by the WCRP for cloud fraction retrievals: about 5% accuracy with height restitution better than 1 km (0.5 km for low clouds) for monthly averages over a 2° by 2° grid. It is well known that clouds often occur simultaneously at more than one level. The radiation budget is considerably influenced by the actual geometrical distribution of the broken cloud fields. This problem is illustrated by figure 2.7, which shows the heating rates as a function of altitude calculated for a single cloud layer in the upper troposphere: adding further cloud layers at other heights would considerably complicate this picture. Taking data from presently available cloud climatologies (having poor height information only), it has been shown that different assumptions on the overlap of clouds occurring at different levels lead to considerably different results. The uncertainty caused by insufficient knowledge on cloud overlap is of the order of 5 to 10 Wm^{-2} for a global average, and can exceed 20 Wm^{-2} in some areas which have a strong regional importance, e.g. the Northern hemisphere stormtracks. This demonstrates that there is a clear need to detect clouds at different height levels simultaneously in order to establish a correct climatology of cloud overlap. Again, this can only be achieved when the active sensors lidar and radar are used.

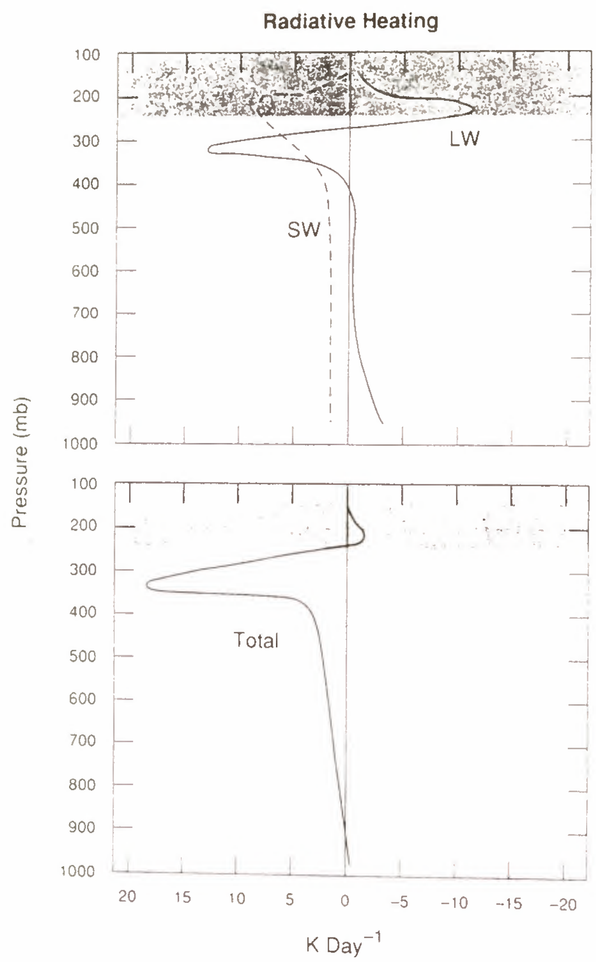

Figure 2.7. *Vertical profile of radiative heating (LW: solid; SW: dashed) for an upper tropospheric cloud (from Salby, 1992).*

Clouds in Polar Regions

In polar regions, clouds are the dominant modulators of radiative flux, and the cloud effects differ substantially from those observed in other regions. Particularly during the polar winter under 'clear sky' conditions, the downwelling longwave flux has been observed to be 10 to 40 Wm^{-2} greater than expected. This has been attributed to the presence of ice crystal precipitation in the lower troposphere. The spatial and temporal distribution of occurrence of this thin 'cirrus' in the lower troposphere can only be observed from space with sufficient coverage. However, it can only be detected with sufficient confidence by a lidar.

A second important feature observed in polar regions is the occurrence of a pronounced stratification in summer-time atmospheric boundary layer clouds. This has a strong influence on the radiation budget, and it is very important that models reproduce this observed phenomenon. As an example, a model assuming a well mixed atmospheric boundary layer would produce only 30% of the cloud cover observed for a layered structure, resulting in a net surface radiative forcing which may be wrong by up to 20 or even 50 Wm^{-2}. Only active instruments can provide observations to assess the importance of these phenomena.

2.2.4. The Sampling Problem

A satellite mission is able to obtain continuous measurements over a large part of the globe. However, for a single satellite, full temporal coverage can only be achieved for a limited area (geostationary orbit), and full global coverage can only be achieved at the expense of temporal resolution (polar orbit). When the parameters to be retrieved have high spatial and temporal variability, which is the case for the radiative properties of the atmosphere, the sampling strategy requires specific attention.

For the ERM, it is proposed that the focus is on the impact of the three-dimensional distribution of clouds and aerosols on the radiation budget and its forcing of the weather and climate systems. Important processes in all regions of the globe need to be studied in more detail. Hence a sun-synchronous orbit (proposed Equator crossing times 2:00 and 14:00 hours) is suggested. While this limits the temporal sampling to early afternoon and midnight conditions, the full range of polar to tropical processes can be observed. To obtain the necessary information on the diurnal cycle of the parameters under study, extensive use should be made of existing observation platforms. The rather complex problem of combining measurements with widely differing sampling and accuracy properties requires the use of modern data assimilation techniques as explained below.

The sampling problem is further complicated because the radiation fields of clouds have an important angular dependence. In fact one of the most important error sources for the determination of the Earth's radiation budget at the top of the atmosphere is the insufficient knowledge of angular dependence functions for the different cloud types in combination with inadequate identification of cloud type (Suttles et al., 1988). Cloud geometrical properties, including the formation of multiple layers, have a strong influence on the angular distribution of the radiation field. The use of lidar cloud top height measurements in combination with imager and scanning radiometer data would give important new information on angular distribution functions for specific cloud types and hence make a major contribution to the improvement of ERB measurements. This would be the main advantage of a scanning lidar as compared to a fixed nadir looking instrument.

The time interval needed to achieve global coverage of the observations depends on the swath width. If individual process studies are not attempted but rather a statistical description of the processes is sufficient, true global coverage is not necessary in the sense that each spot of the globe is actually observed within a short period of time. It is only necessary to sample all important regions of the globe. There are important advantages if scanning capability is provided for the lidar and the passive instruments. The measurement of monthly mean cloud fractional coverage has been shown to yield better accuracy for a scanning lidar as compared to a nadir looking instrument, in particular for high clouds, where the improvement is more than a factor of two. Full cloud modelling requires three-dimensional cloud structure for given scenes, but it is dubious whether this can be derived from a two-dimensional cross-section. The latter may suffice in a statistical sense, but certainly not for individual cases.

2.2.5. Regional Versus Global Observations

The expected improvement of imager data interpretation arising from the use of a lidar and a cloud radar opens new interesting perspectives for regional atmospheric energetic and process studies where the appropriate space-time observations are available from geostationary satellites. Indeed, regional atmospheric observations are often focused on furthering the understanding of the mechanisms induced by geography or orography due to surface inhomogeneities as well as the availability of energy sources and sinks subject to diurnal variation. The monsoon effects over the gulf of Bengal, the desertification over the Sahel and the meteorology of the Alps are a few examples.

At the regional scale, due to the existence of some long time series of observations, measurements at certain sites have allowed objective estimates of climate change to be made. At the global scale, however, a change in one region can be compensated by an opposite change in another region and the situation becomes more complex and, hence, difficult to model.

2.2.6. Coupling of Radiation to Dynamics

In the ERM it is proposed to combine passive radiation measurements with active instrument data to provide significant and essential new information on the three-dimensional distribution of the diabatic heating in the atmosphere which drives the atmospheric circulation. Radiation is not the only factor governing climate and climate change. Atmospheric and ocean dynamics determine how the excess of heat input (corresponding to positive radiation balance) at lower and summer latitudes is transferred to zones of negative radiation balance. However, the radiation field is a sensitive, direct indicator of changes to the planetary energy balance, and studies of radiative parameters are sometimes sufficient to determine heat and water transport. Satellite observations of annual zonal mean net radiation and its pole-to-equator gradient, together with 'classical' meteorological determinations of atmospheric meridional heat transport, have yielded estimates of meridional heat transport by the oceans which are in disagreement with some estimates by oceanographers (Carissimo et al., 1985); these issues are still to be resolved. Although the outgoing LW radiation is often used as a diagnostic of atmospheric effects of ENSO events, the role of radiative feedback, at the sea surface and as a function of altitude, has barely been investigated. As already noted above (section 2.2.3), the three-dimensional distribution of diabatic heating in the atmosphere depends on the sum of the radiational heating/cooling terms and the release of latent heat corresponding to the condensation of water vapour in clouds. By providing precise cloud height determinations unaffected by semi-transparency in the infrared, the active instruments on board the ERM will yield significant improvements in height assignments of winds based on cloud displacement vectors observed from geostationary weather satellites. This is a necessary condition for accurate estimates of wind field divergence.

Recent theoretical work (Rahmstorf, 1995) suggests that the North Atlantic deep water formation may be near the limit of stability, and there has been some speculation that global warming could lead to a halt of the thermohaline ocean circulation. Although this may be considered to be a question only of ocean dynamics, the implications for the climate of western Europe clearly depend on how changes in latent and sensible heat over the Northern Atlantic will be conveyed to the continent. It is argued that this will be achieved through changes in the structure of the atmosphere and the distribution of clouds. Again, short of waiting for the 'experiment' to run its course, the best chance to make reliable model predictions is to evaluate the behaviour of these models by reference to observations of 3-dimensional atmospheric and cloud field changes.

2.2.7. Modern Data Assimilation Techniques

In the study of a system as complex as the climate, it is important to remember the need to subject theoretical ideas and model simulations to the test of comparing them with observations. In recent years, much work has been done, especially by the meteorological community, on the optimum use of observations and computer models, with a view to obtaining the best from each. Against this background, the idea of 'data assimilation' has developed. The basic idea is to operate on a running computer code which simulates the atmosphere (or the oceans, or both), and to use the observed fields of key parameters (temperature, winds, humidity, in the case of meteorological forecasting) to force the corresponding calculated fields within the model (Eyre et al., 1993). In practice, the simulated and observed parameters are usually combined with relative weightings which reflect the uncertainties (errors) associated with each.

In the case of the ERM, it will be important to access this technique, in order to make the most of the new observations. Thus, observations of cloud height and structure may be used to force similar parameters within a general circulation model (GCM), in which radiative parameters such as flux divergence and heating rates can be represented. Clearly, this will not be an operational process as is the case in weather forecasting. Nevertheless, such techniques will have an important application to the novel observations to be obtained from ERM. These ideas of data assimilation techniques also have important application for the ERM which will have to combine data from different sources.

2.3. Mission Aims

As shown in this chapter a large number of key scientific problems exist which undermine the understanding of the radiative properties of the Earth's climate system. It has been shown that some of the most serious causes of uncertainty are related to the almost complete inability to measure, and consequently to model with any assurance, the vertical structure of cloud, aerosol, and radiative fluxes, especially in situations of complex, multiple cloud layers. Complex structures like this can have major influence on the distribution of radiative heating and cooling in the atmosphere, on atmospheric dynamics, and, in the long term, on the state of the climate. The Earth Radiation Mission, ERM, is intended to make a unique contribution to the solution of these problems.

3. Research Objectives

3.1. Requirements for Earth Radiation Data

Transformation of energy is the driving process in the Earth atmosphere. In a simplified model, incoming shortwave radiation is absorbed or reflected by the atmosphere (clouds, aerosols) or the Earth surface (land, oceans). Absorbed energy is re-emitted or reflected by atmospheric trace gases or clouds (atmosphere) or transformed into sensible and latent heat (Earth`s surface) which drive atmospheric processes like condensation and cloud formation. The dominant forms of energy involved in these processes are radiation, latent and sensible heat. Latent and sensible heat are transformed within the atmosphere. Radiation is the only process by which the Earth and its atmosphere exchange energy with deep space.

There is thus a need to understand the role of the Earth's radiation budget (ERB):

- in maintaining the present climate;
- in governing the amplitude and evolution of large-scale climate anomalies;
- in determining how climate changes in response to perturbation.

This requires a better ability to determine the vertical profiles of the Earth radiation budget together with the surface radiation budget implying:–

- an improvement of knowledge of the role of atmospheric constituents, in particular clouds and aerosols as well as water vapour, in maintaining and modulating the Earth radiation budget taking into account feed-back mechanisms;
- an increase in the understanding of feedbacks between surface and atmospheric processes, in particular the role of snow and ice.

3.2. Problems with Existing and Planned Data Sources

Although much has been accomplished in some of these areas over the past 20 years, existing data sources have many shortcomings.

1) Measurements of broad-band radiative fluxes have *not* been systematically associated with high-resolution narrow-band imager data allowing precise cloud identification. As a result the angular correction procedures and studies of cloud-radiation forcing and interactions are generally only valid in a statistical sense. Although the ERBE scanners flew together with AVHRR and TOVS on NOAA-9 and -10, the ERBE angular models were designed in terms of the ERBS payload, using only the coarse-spatial-resolution broad-band ERBE measurements and not the real-time AVHRR and TOVS data for scene identification and choice of angular models. Thus high random errors affect

individual measurements needed for process studies, and bias cannot be excluded. Although the planned CERES/MODIS combination planned for EOS will improve this situation, *it still will only provide top-side view cloud information.*

2) Cloud studies rely essentially on the ISCCP and the surface cloud climatologies. Neither of these provides full information on the vertical distribution of clouds. For those clouds that can be seen from space, estimates of cloud top heights are available, but they can be seriously in error. Although the use of TOVS sounder or MODIS narrow bands should allow some improvement, the weighting functions in these channels remain too broad for precise height assignment. Moreover, the attempts to deduce multi-layer cloud properties are strongly sensitive to radiative transfer modelling assumptions and so will be very uncertain. Cloud characterization over snow or ice surfaces remains unsatisfactory.

3) The only global data available on aerosols relate to aerosol layers over oceans and to some extent over other dark surfaces. Practically no data exist about the important aerosol layers over snow/ice and desert surfaces, and over or in between cloud layers. Even when the presence of aerosols is clearly detected (usually only by day over ocean), precise height assignment is practically inexistent.

3.3. The Unique Contribution of the Earth Explorer Earth Radiation Mission

Taking note of the foregoing discussion, the primary objective of the Earth Explorer Earth Radiation Mission, ERM, is

- to provide data essential for the quantification of key radiative processes which control the Earth's climate system, and
- to provide data essential for the improvement and validation of the general circulation models used to predict the response of climate to anthropogenic perturbations of the Earth's radiation budget.

The Earth Explorer Earth Radiation Mission is intended to provide a picture as complete as possible of the 3-dimensional spatial and the temporal structure of radiative transfer at the top of the atmosphere, within the atmosphere, and at the Earth's surface. The reason for this, as outlined in chapter 2, is that radiative properties of the atmosphere are to a large extent determined by the distribution of humidity, clouds and aerosols. It is the main goal of this mission to quantify the impact of cloud and aerosol fields associated with a number of atmospheric processes on the radiation balance, globally as well as regionally. Only with such a detailed knowledge about the relevant features of the present state of the atmosphere it will be possible to constrain general circulation models in such a way that they can yield reliable predictions of future climate developments.

4. Observational Requirements for the Earth Explorer Earth Radiation Mission

4.1. Overview

To meet the objectives of the Earth Explorer Earth Radiation Mission the following observations are required:

1) The fundamental data needed include the reflected SW and outgoing LW fluxes at the top of the atmosphere, and the upward and downward SW and LW fluxes at the surface. Note that although fluxes at the top of the atmosphere are determined relatively directly from satellite radiance measurements, their accuracy depends in part on angular corrections requiring the identification of cloud cover. This is particularly important for the estimation of cloud radiative forcing, which depends on the accurate identification of cloud-free areas.

2) The determination of SW and LW fluxes at the surface and at various levels (typically 10) within the atmosphere requires knowledge of the vertical profiles of temperature and humidity. It also requires, over the 60% of the Earth's surface that is covered by clouds at any time, *accurate determination of cloud cover, of the number, thickness and height of cloud levels,* including degree of overlap, cloud macro- and micro-physical properties (optical thickness, particle number and sizes, liquid/ice water content). Information on radiatively active non-water aerosol layers is also important.

Such knowledge is essential because cloud-radiation feedbacks are a critical source of uncertainty in the estimation of climate sensitivity to perturbations, in particular to the known and growing anthropogenic perturbations of radiation balance by carbon dioxide, methane and aerosols. The cloud-radiation feedbacks built into climate models depend critically on model parametrizations of the conversion of water vapour to clouds and of cloud-radiation interactions (e.g. Senior and Mitchell, 1993). The aerosol distribution has been shown to have an important influence, both directly in reflecting SW radiation and indirectly by increasing the albedo of certain cloud fields.

An overview of the observational requirements is given in figure 4.1.

Specifically, in order to meet the goals of this mission, the following key parameters have to be measured:

- SW and LW radiative fluxes at TOA;
- cloud top and base heights;
- cloud type;
- cloud fractional coverage;

- cloud optical thickness;
- liquid or ice water content;
- effective particle size;
- aerosol layer top/base heights;
- aerosol optical thickness.

The presence of multiple layers must be explicitly considered, and the corresponding parameters must be retrieved for each individual layer.

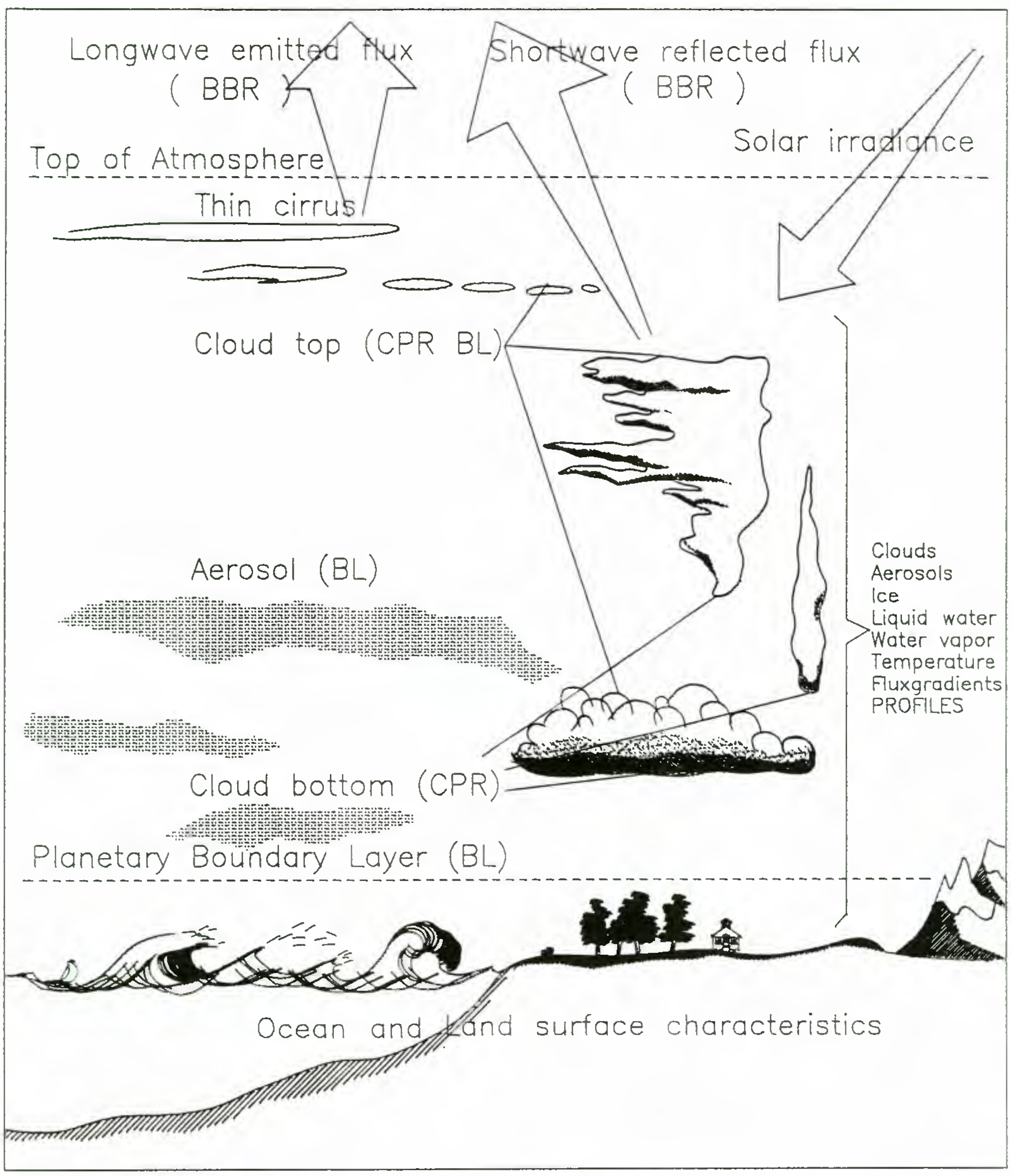

Figure 4.1. *Schematic of the observational requirements of the Earth Explorer Earth Radiation Mission, ERM (BBR = broadband radiometer, BL = backscatter lidar, CPR = cloud profiling radar).*

4.2. Accuracy Requirements

The accuracy which is required for the measurement of the parameters listed above is derived from the impact they have on the radiation budget at the top or at the bottom of the atmosphere. For the fluxes at the top of the atmosphere, TOA, the numbers are given in table 4.1.

Measurement objective	**Spatial scale**	**Temporal scale**	**Accuracies of SW and LW fluxes at TOA (Wm^{-2})**
global radiance balance	global	seasonally	1 - 3
regional climate variability (e.g. ENSO)	100 - 250 km	monthly	2 - 5
detailed studies (e.g. cloud radiative forcing)	35 - 250 km (or pixel)	composites or instantaneous	5 - 10

Table 4.1. *Required accuracies for SW and LW fluxes at the top of the atmosphere.*

Parameter	**Spatial Scale**	**Desired accuracy (or detection limit)**
SW and LW flux at TOA	50×0 km^2	5 - 10 Wm^{-2}
Layer tops/bottoms	50×5 km^2	0.2 km
Cloud fractional coverage	50×5 km^2	5%
Cloud optical thickness	50×5 km^2	0.1 (detection limit)
Liquid/ice water content	50×5 km^2	0.2 g m^{-3} (detection limit)
Effective particle size	50×5 km^2	(to be defined)
Stratospheric aerosol optical thickness	1000×100 km^2	0.1
Boundary layer aerosol optical thickness	50×5 km^2	0.1
T/H_2O profiles	50×5 km^2	1 K / 10 % rel. humidity
Surface emissivity	50×5 km^2	0.03

Table 4.2. *Desired rms accuracies of parameters to be measured within the atmosphere.*

Since the radiation budget components are influenced in a variety of ways by the highly variable cloud fields associated with very different processes in different areas of the globe, the links between the accuracy needed for cloud and aerosol parameters and the accuracy of the radiation quantities cannot be quantified properly. However, for the purposes of this mission it is necessary to establish some target values. These are given in table 4.2. To achieve this, the contribution to the variation in the estimates of TOA radiances from individual processes has been calculated. In so doing, the aim has been to ensure that they do not contribute to a variation larger than the 4 Wm^{-2} change which would arise in surface flux (e.g. as a result of global warming due to carbon dioxide (IPCC, 1994)), or the 10 Wm^{-2} or so uncertainty due to cirrus and global albedo. In such a complex system, these figures provide a reasonable guide to the required accuracies of instrument observations.

4.3. Observational Requirements

To address the requirements detailed in sections 4.1 and 4.2 poses a major challenge which cannot be satisfied by a single observing system. As shown in table 4.3 it is possible to

	BBR	BL	CPR	CI	GI	MI	IS	MS
SW/LW flux at TOA	X							
Layer tops		X	X	(X)	(X)		X	
Layer bottoms		(X)	X					
Cloud fractional coverage		X		X	X	X		
Optical thickness		X	(X)	X	X	X		
LWC/IWC			(X)			X		
Effective particle size			(X)			(X)		
Aerosol coverage		X						
T profiles							X	X
Water vapour profiles					(X)	X	X	X
Surface temperature				(X)	(X)	(X)	(X)	(X)
Surface emissivity				(X)	(X)	(X)	(X)	(X)

Table 4.3. *Observational requirements related to instruments*

Key: BBR = Broadband radiometer; BL = Backscatter lidar; CI = Cloud imager; CPR = Cloud profiling radar; GI = Geostationary imager; IS = Infrared sounder; MI = Microwave imager; MS = Microwave sounder; X = parameter directly derived from instrument; (X) = parameter derived using auxiliary data.

envisage several instruments contributing to the realisation of the mission objectives. It should be noted that, with the exception of the cloud radar and the backscatter lidar, these data should be made available from existing (or planned) sources. It is clear that the provision of a backscatter lidar and a cloud profiling radar are of fundamental importance for the ERM. Theses two instruments are described in the following.

4.3.1. Backscatter Lidar

The backscatter lidar is needed for the retrieval of parameters associated with optically thin layers, in particular aerosol and thin clouds (e.g. cirrus), as well as the precise determination of the heights of the upper cloud layers. With the lidar, radiation is measured which is backscattered from the cloud and aerosol particles contained in the measurement volume. This volume is determined by the length of the laser pulse transmitted into the atmosphere. The location of that measurement volume is very precisely determined by the travel time of the light pulse from the transmitter to the backscatter region and back to the receiver. A height resolution of 15 m can be achieved, though the realisable accuracy is mainly determined by the necessary averaging due to signal-to-noise considerations and attitude control of the spacecraft. These are discussed in chapter 6.

The lidar signal (backscattered power) is linked to the atmospheric parameters through the (simplified) lidar equation:

$$P(r) = C\, r^{-2}\, \beta(r)\, T(r) \qquad (4.1)$$

where P(r) is the backscattered power from range r, C an instrument constant, ß(r) the backscatter coefficient at range r, and T(r) the two-way transmission on the atmospheric path from the spaceborne transmitter to the probed volume and back to the receiver.

The inversion of this equation in order to derive atmospheric backscatter and/or extinction from the measured signal has been studied extensively in the context of ground based or airborne lidar applications for more than 20 years (Russell and Morley, 1982). There is also some experience with data from a spaceborne backscatter lidar, resulting from the LITE mission (NASA's shuttle experiment for demonstration of the lidar in space technology). The results obtained so far demonstrate very clearly, that a spaceborne lidar should be capable of measuring the parameters required to address the Earth Explorer Earth Radiation Mission objectives over a large range of atmospheric conditions (Winker et al., 1996)

The cloud top determination from lidar measurements does not depend on details of the inversion procedure as the signal even from very thin clouds is orders of magnitude larger than the signal from molecular scattering or background aerosol. However, the retrieval of the optical depth of thin clouds requires the use of some general scattering properties of cloud particles, for which a database is presently being established in the frame of the Experimental Cloud Lidar Pilot Study (ECLIPS) project.

For the lidar instrument a scanning capability is highly desirable, because this will strongly increase the quality of the retrieved datasets of 3-dimensional cloud and aerosol distribution. However a valuable mission would be achieved even with a nonscanning lidar.

4.3.2. Cloud Profiling Radar

The cloud profiling radar is the sole instrument capable of providing high vertical resolution data of internal cloud layer structures within the atmosphere. The operational principle of such a radar does not differ from other ground-based or aircraft-based weather radars.

For non-precipitating clouds, the typical sizes of ice or water particles are substantially smaller than the radar wavelength, so, the wave scattering occurs in the so-called Rayleigh region. The corresponding per-unit-volume reflectivity η of a cloud is given by:

$$\eta = 10^{-6} \pi^5 \lambda^{-4} |K|^2 z \qquad (4.2)$$

where

λ: radar wavelength [mm]
K: dielectric factor of cloud particles (complex number)
z: $z = \int D^6 N(D)\, dD$ [$mm^6 m^{-3}$], where D is the particle diameter [mm] and N(D) is the particle size distribution [m^{-3}]. Often z is given in decibel: dBz = 10 log z, with z in $mm^6 m^{-3}$.

Radar wavelength: Due to the small particle sizes of non-precipitating water and ice clouds (mean diameter from 2 µm to 1000 µm), a short wavelength is necessary in order to achieve sufficient sensitivity. On the other hand, the signal attenuation along the propagation path increases with decreasing wavelength (major contribution due to water vapour and cloud absorption). When both the radar power and antenna size are limited, the optimum frequency appears to lie within the atmospheric window centred around 90 GHz.

Horizontal resolution: There is a non-linear relationship between the optical depth of a cloud and its radar reflectivity. An averaging of horizontal cloud field with some variability by a large radar footprint would introduce measurement biases which can no longer be corrected by subsequent data processing (a so-called non-uniform beam filling effect). In order to minimise such biasing effects, the size of radar footprint needs to be comparable or inferior to the smallest horizontal cloud structure (in an optical sense). This means that a horizontal resolution of 1 km or less is required, which corresponds to the smallest correlation length of typical clouds.

Particle size distribution, LWC and IWC: Since the cloud reflectivity is proportional to a weighted sum of the particle diameters to the power of six, it is in general not possible to recover the particle distribution from the backscattered signal alone. Hence, no direct measurement of LWC or IWC will be possible. Accurate inversions of the data require complementary information provided by the other instruments. For instance, a simultaneous measurement with the backscatter lidar of thin clouds and the top layers of other clouds provides information which can be used to constrain the solution of the particle size in the inversion equation as a lidar effectively adds an additional sensing frequency (dual-wavelength technique).

The information on cloud phase (ice and water) can be inferred from radar measurements because of variations in attenuation. At 94 GHz typical values of Im(-K), which determines the attenuation, are Im(-K) = 0.2 for water and Im(-K) $< 10^{-5}$ for ice. Using the so-called 'surface reference technique' (Marzoug and Amayenc, 1991) attenuation can be estimated from a radar echo from the Earth's surface.

Cloud bottom, ground clutter and blind layer: The reliable detection of cloud bottom requires two conditions to be fulfilled:

1) no excessive attenuation of the radar signal along the propagation path down to the cloud bottom – this implies that no measurement of clouds is possible below the top of a rain (e.g. melting layer).

2) no contamination of the backscattered signal by ground clutter (range ambiguity problem) – this imposes requirements on the shape of the radar pulse: assuming a rectangular pulse of duration τ, the range resolution of the radar is given by $\Delta R = c\tau / 2$, where c is the velocity of light.

The minimum measured altitude assuming a nadir pointing radar is then $\Delta R/2$. The altitude range between ground and $\Delta R/2$, which is masked by the ground clutter, is called 'blind layer'.

These instruments would need collocated observations from the broad-band radiometer and the cloud imager.

4.3.3. Orbit

The temporal sampling and the global coverage characteristics of the measurements are strongly linked with the choice of the orbit of the space platform as mentioned in sub-section 2.2.4, a sun-synchronous orbit with Equator crossing times at 02:00 and 14:00 hours local time is recommended. This orbit has the advantage of providing an excellent global coverage, in particular including the polar regions, and providing measurements for fully developed day-and night-time conditions. It is intended that the limited temporal coverage caused by this choice of orbit will be compensated by the use of additional data from operational satellites, as will be explained below.

4.3.4. Duration of the Mission

Regarding the duration of the mission, measurements over a period of 4 years should be sufficient to provide statistically meaningful data needed to address the mission objectives.

5. Mission Elements

5.1. The Elements of the Earth Explorer Earth Radiation Mission

In order to meet the scientific requirements elaborated previously, it is proposed that the Earth Explorer Earth Radiation Mission, (ERM), will comprise two elements:

1) a set of instruments to be deployed on the satellite which is proposed to be called GRACE (Global Radiation, Aerosol and Cloud Explorer), and designed to make measurements of the vertical structure of cloud, and aerosols, and to provide the imagery and radiometric data required to interpret these data; and

2) a set of auxiliary measurements, utilising observations made by operational satellite missions, from the ground, and elsewhere.

The main elements of the GRACE payload will be a lidar and a cloud radar. These will need to be complemented by a broadband radiometer and a passive imager. The payload of GRACE will therefore be:

- A backscatter lidar to observe the characteristics of aerosol and thin cloud layers as well as cloud top heights;
- A cloud profiling radar for the retrieval of the geometrical properties of thick clouds, LWC/IWC distribution within the clouds, and precipitation ;
- A broadband scanning radiometer to measure SW and LW fluxes at TOA;
- A visible/infrared (VIS/IR) cloud imager to provide the link to standard measurements as made from operational platforms (i.e. cloud fractional coverage, aerosol optical thickness, layer tops, surface temperature and emissivity), and to provide the necessary information for interpolating the fields measured with the different instruments having different sampling properties;

plus a GNSS receiver to provide atmospheric profiles of temperature and water vapour.

The orbit is a circular, sun-synchronous orbit at an altitude of about 600 km. The repeat cycle is 22 days, Equator crossing time is 1400 hrs. The baseline mission duration is 4 years.

5.2. Ground Segment

Section 6.6 describes the ground segment in more detail. In summary the ground segment will consist of a dedicated single ground station and a centre for the engineering pre-processing of the data and archiving. The scientific processing will be performed by a separate centre.

The whole data reduction process is not time critical (typical delivery times would be 1 to 2 weeks). Data should be archived for 10 years.

5.3. Supporting Mission Elements

5.3.1. Geostationary Elements

The geostationary, operational Earth observation platforms of the Meteosat Second Generation (MSG) series will provide for each location, observed at a fixed angle; the day and night variations of cloud coverage; cloud and surface discrimination and classification (fog, low clouds, aerosols, cirrus, snow); water vapour distribution; cloud top, land and sea surface temperature; the cloud motion vector; and cloud top pressure estimation. In addition, the reflected solar irradiation and emitted infrared radiation will be observed for the first time with excellent temporal sampling (every 15 minutes) by the GERB instrument. The high resolution images provided by the MSG SEVIRI instrument will assist in the identification of the cloud field. In addition, geostationary satellites operated by other agencies, GOES, GMS, INSAT and GOMS geostationary satellites would provide the classical visible (0.5-0.75 μm) and infrared (10.5-12.5 μm) observation channels.

5.3.2. Low Earth Orbiting Elements

GNSS receivers to provide high vertical but low horizontal resolution profiles of temperature and water vapour in the upper troposphere and in the stratosphere could be embarked on various low Earth orbiting satellites.

Observations of cloud ice and liquid water content and of the Earth's surface under cloudy conditions could be provided by microwave imagers embarked on other satellites in low Earth orbits.

5.3.3. Objective Analyses

Products provided by objective analyses (temperature, water vapour profiles) would contribute to achieving the mission objectives of the Earth Radiation Mission.

5.3.4. Surface Observations

The routine observations required would be synoptic temperature, pressure and humidity. To this information surface cloud radar observations could be added.

5.4. Support to Other Missions

The Earth Explorer Earth Radiation Mission would provide data of the Earth's surface which could be useful for the Earth Explorer Land-Surface Processes and Interactions Mission (ESA, 1996a). It could provide surface temperature and emissivity data in cloud-free areas. The mission would also support the Earth Explorer Precipitation Mission (ESA, 1996b) by providing observations of non-precipitating clouds, cloud top and bottom heights. More generally, the observations of the 4-dimensional cloud fields on a global basis could be of great value to meteorology and weather forecasting, as a complement to operational satellite systems.

6. System Concept

6.1. GRACE Payload

The GRACE has a baseline payload consisting of the instrument package as defined in chapter 5. This payload concept provides a maximum of synergy while satisfying the observational needs. Use has been made of existing instruments to the extent possible in order to minimise developments. Some adaptations of instruments' fields of view and spatial as well as temporal sampling patterns will be required to meet the specific needs of this mission; relevant details are found in the sections below.

Figure 6.1 schematically shows the footprints of the four instruments. The broadband radiometer and the cloud imager provide horizon-to-horizon coverage, while the lidar samples a much smaller swath in a sinusoidal manner. Coverage of the cloud radar is limited to profiling of the ground track above nadir. The instruments are synchronised via their sampling speeds. The cloud radar will operate at a pulse repetition frequency lying in the KHz range enabling it to cover the same area as the lidar (at the same time). The same applies to the broadband radiometer and the cloud imager as they cover the swaths of the active instruments completely.

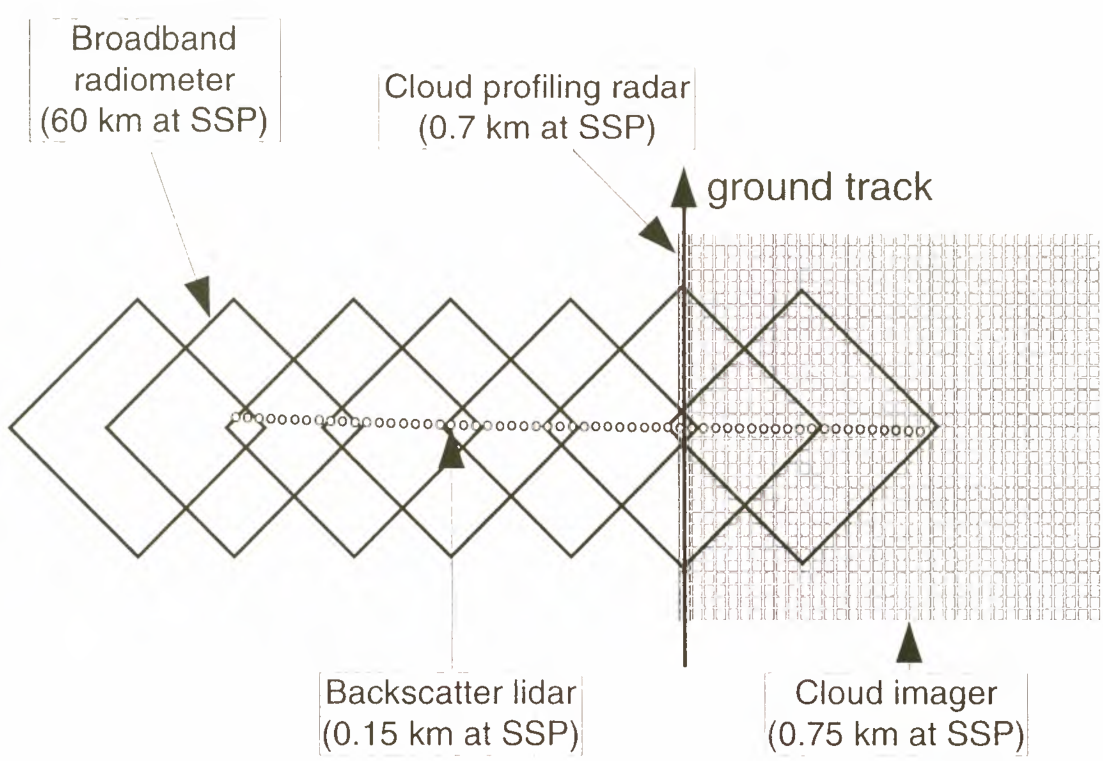

Figure 6.1. *Footprints of the Earth Explorer Earth Radiation Mission Instruments*

6.1.1. Broadband Radiometer

Instrument Objectives

The broadband radiometer is required to provide the outgoing components of the Earth's radiation budget at the top of the atmosphere (TOA), i.e. the SW reflected and the LW emitted fluxes.

For the purposes of this assessment ScaRaB has been assumed for which two concepts exist, i.e. one for METEOR/RESSURS and one which was considered for ENVISAT/METOP.

Instrument Description

ScaRaB is a four channel radiometer which can measure the radiation reflected and emitted by the atmosphere. The 'total' channel covers the spectrum from 0.2 to 50 μm. The 'solar' channel determines the reflected radiation in the range 0.2 to 4 μm. In addition, longwave infra-red radiation is measured by a channel sensitive in the 10.5 to 12.5 μm band. A further channel covers the visible part of the spectrum between 0.5 and 0.7 μm or 0.6 to 4 μm depending on the concept.

The instrument consists of four single mirror telescopes rotating across-track in a common scanning assembly. The rotation is divided into an observation swath of +/- 56° and some discrete positions for calibration. A filter wheel is placed in front of the total and solar channels to select the spectral responses for measurement and calibration modes. Reflective choppers are used in front of the telescopes to provide alternating access to the scene and to a reference black body at the pixel repetition rate.

For METEOR, flying at an altitude of 1200 km, the pixels have a size of 50 mrad (60 km at nadir) square diagonally aligned on a grid of approximately 35 mrad (42 km). In the proposed ENVISAT/METOP configuration 40 × 5 mrad (32 × 40 km) pixels were aligned on a parallel grid with 40 mrad spacing.

Calibration is performed for METEOR/RESSURS using black bodies and lamps. For ENVISAT/METOP the calibration devices were redesigned by omitting all lamps and using black bodies for the 'total' and 'window' channels and using a transmission silica diffuser for the 'solar' channel. The accuracy of the ENVISAT/METOP version was estimated at about 2.5% for the short wave and about 3.8% for the longwave components.

Instrument Interfaces

The instrument requires a large unobstructed field of view for measurement and calibration. This can be achieved by means of mounting ScaRaB on the top of a pedestal.

Resource requirements are about 50 kg and 50 W; the data rate is 3 kbps.

Instrument Development Status

Both instrument configurations would need modification for use on GRACE.

As a minimum, the scanning mechanism would need to be adapted to provide contiguous pixels from a 600 km orbit. This could readily be achieved by reducing the scanning period from 6 s to 4.5 s. However a review of the requirements for pixel orientation, sampling and overlap need to be conducted as well to arrive at an optimum configuration.

The METEOR/RESSURS configuration was not optimized in terms of the technology employed in its basic design. The ENVISAT/METOP configuration, although available only as a concept, would not suffer from this drawback and should be selected as the baseline.

6.1.2. Atmospheric Backscatter Lidar

Instrument Objectives

ATLID is a backscatter lidar concept which measures profiles of optically thin clouds and aerosol layers and cloud boundaries with a high vertical accuracy night and day. ATLID has been designed to provide a 3-dimensional mapping of optically thin clouds at the top of the atmosphere, thick cloud top heights and their horizontal extent as well as the height of the planetary boundary layer (PBL).

The instrument transmitter emits a short duration pulse towards the atmosphere at a given wavelength. Atmospheric particles backscatter part of the incident light which is collected by the instrument telescope and measured by a photo detector. The range to the atmospheric targets and their optical properties are determined from the pulse time of flight and the backscattered signal power measurements. Two-dimensional sampling of cloud fields is achieved via scanning of the instrument's line of sight as illustrated in figure 6.2.

Table 6.1 summarises the ATLID performance requirements.

For the assessment of the conceptual instrument performance, the ATLID reference model of the atmosphere (ARMA) has been defined, which is based on ground based lidar measurements reported in the literature. The atmospheric targets, which are the drivers for the instrument design, are optically thin cirrus and the top of a clear PBL on a summer day. The ARMA backscatter coefficients for these two targets are respectively $1.4\ 10^{-5}$ and $5.0\ 10^{-6}\ m^{-1}\ sr^{-1}$. The ARMA extinction coefficients are $2.0\ 10^{-4}$ and $1.6\ 10^{-4}\ m^{-1}$ while their vertical thicknesses are 1000 metres and 500 metres respectively.

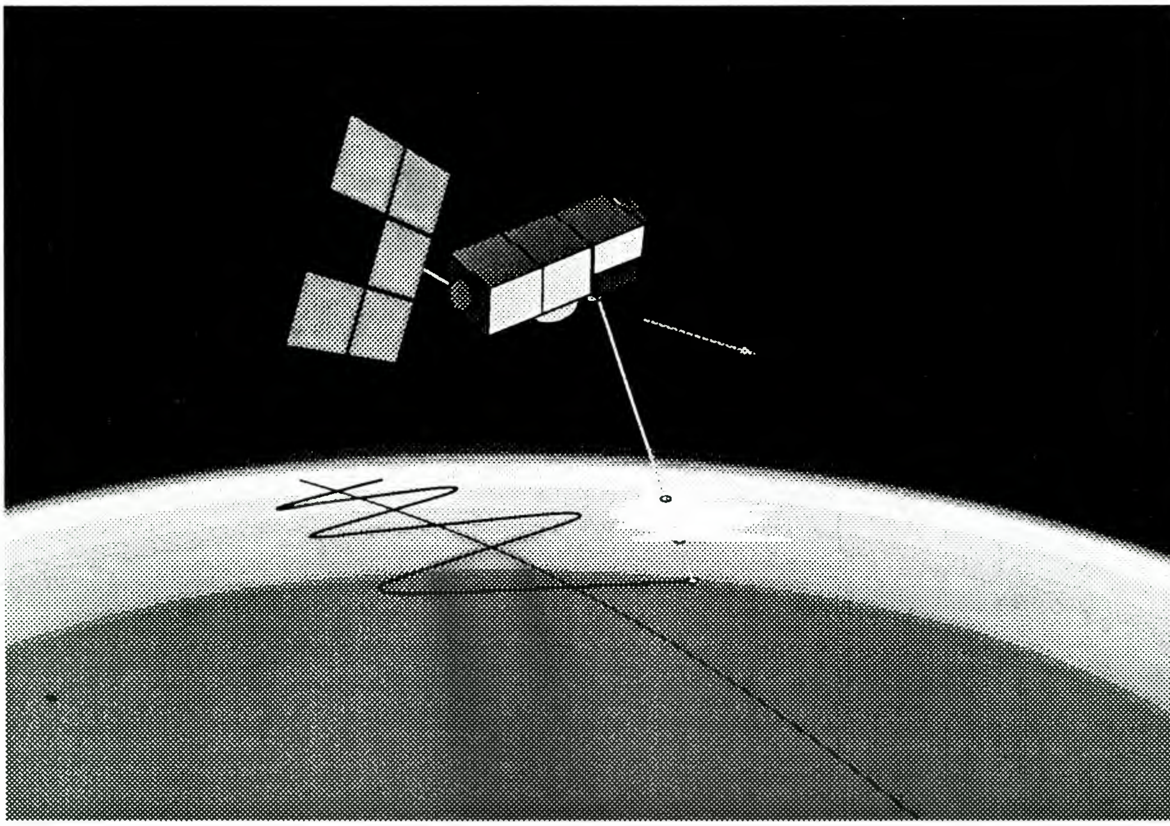

Figure 6.2. *ATLID Scan Pattern*

Instrument Description

The architecture of the ATLID instrument concept features a laser transmitter, an opto-mechanical subsystem and a receiver. The laser transmitter is a pulsed Nd:Yag laser mounted with the receiver and its drive mechanism on a dedicated structure panel located on one side of the telescope. A scanning mechanism actuates the mobile telescope following a sinusoidal motion. A contra-rotating flywheel is used to balance the torque induced by the telescope. The outgoing beam is directed to Earth by a small mirror attached to the scanning assembly. The mobile part is optically linked to the fixed part by passing the outgoing and return beams through the hollow optics-side bearings. A roll axis star sensor is attached to the instrument to restitute the laser line of sight and retrieve accurately target altitude. The general configuration is shown in figure 6.3.

Item	Requirement	Comments
General requirements		
Wavelength	1064 nm	
Observation range	0-25 km 100-150 km	useful range calibration range
Earth coverage	≤ 7 days	day and night independently
Lifetime	≥ 4 years	
Geometrical requirements		
Vertical resolution	50 m	depends on the sampling frequency and target characteristics
Height accuracy	± 100 m (3 σ)	altitude restitution accuracy
Shot location accuracy	± 2000 m (3 σ)	horizontal location restitution accuracy, edge of swath
Radiometric requirements		
Cloud top	SNR > 3 on single shot	except for cirrus
Cirrus top and bottom	SNR > 3 over 35 × 3 km^2	shots are accumulated and averaged over the specified area to obtain the required SNR
PBL top	SNR > 6 over 100 × 10 km^2	

Table 6.1. *ATLID Performance Requirements*

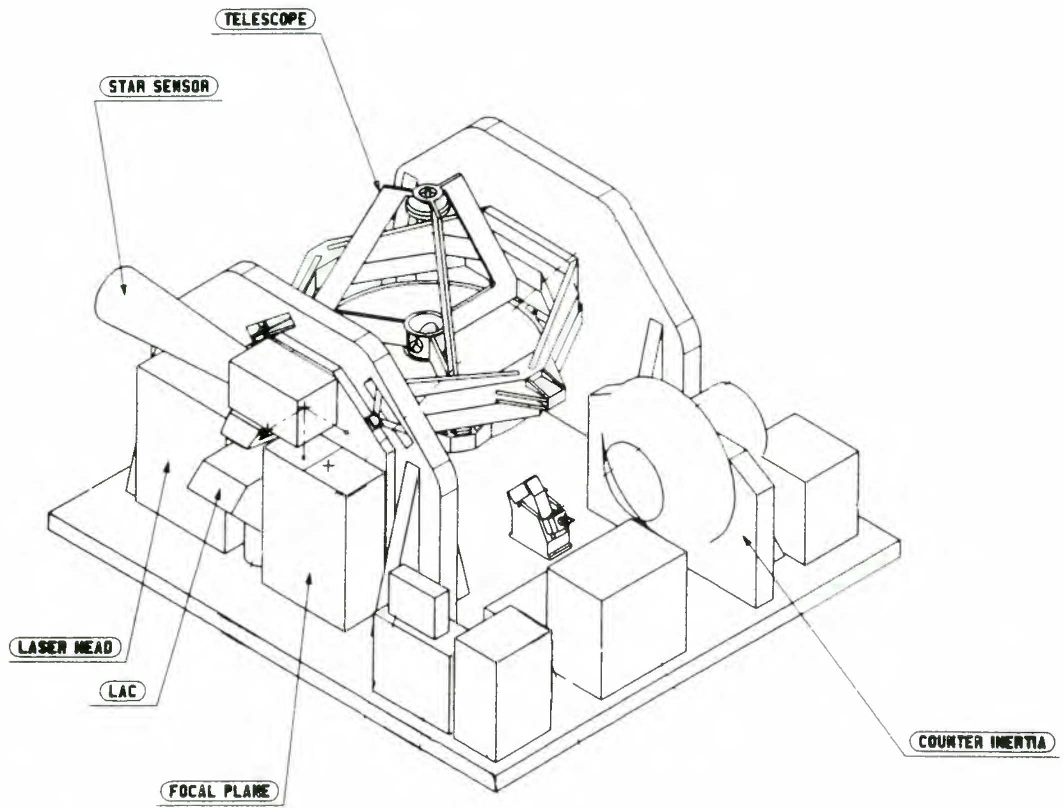

Figure 6.3. *ATLID General Configuration*

The transmitter is an all solid state Nd:Yag laser oscillator operating in pulse mode by means of an electro-optic Q-switch. It is diode-pumped to satisfy lifetime, output efficiency and compactness requirements and emits a polarized pulse beam of 100 mJ at a wavelength of 1064 nm with a repetition rate of 100 Hz. The spectral quality (narrow line width and line stability) of the transmitter is important in ATLID design because the laser is used in combination with a very narrow optical band filter (~0.3 nm) for the rejection of scattered sunlight. The implementation of a second laser head is envisaged to comply with the reliability requirement for a 4 year mission.

The telescope assembly concept is a Cassegrain type with a flat folding mirror. The telescope's primary mirror has a 600 mm aperture and is made of lightweight material to limit the inertia of the mobile part.

Before photo detection, the optical signal collected by the telescope is transmitted via relay and focal plane optics where a physical aperture limits the instrument field of view and together with the combination of a Fabry-Perot filter and a narrow band dielectric filter reduces the contribution of scattered sunlight to the return signal.

The filtered optical signal is transformed into an electrical digital signal by the detection chain. It consists of a thermoelectrically cooled avalanche photodiode in a transimpedance amplifier configuration with two parallel analog processing chains. The radiometric chain is optimized for high sensitivity (thin clouds), with a low electrical bandwidth (1 MHz) while the peak detection chain is optimized for short and strong pulse detection (dense clouds) with a high sampling rate (8 MHz) and threshold detection.

The pointing subsystem consists of the scanning assembly with a torque motor and a precision angular encoder, a flywheel for torque compensations, a roll sensing star sensor to restitute the absolute transmitter line of sight and a lag angle compensator. The lag angle compensator ensures that the return backscattered signal enters the instrument field of view while the telescope is scanning. The lag angle compensator is a controlled two-axis beam steering device inserted in the transmitter optical path. It aims the transmitter line of sight at the predicted direction of the telescope line of sight during reception time. The lidar can be operated in a non-scanning mode at any position within its field-of-view.

A two phase fluid loop with a capillary pump dissipates the heat generated by the laser to space via a radiator and controls the laser temperature to ensure its performance stability.

Instrument single shot performance estimation for various observation conditions is shown in figure 6.4. The swath width is 470 km for a sun-synchronous 600 km orbit providing daytime or nighttime Earth coverage in less than 7 days.

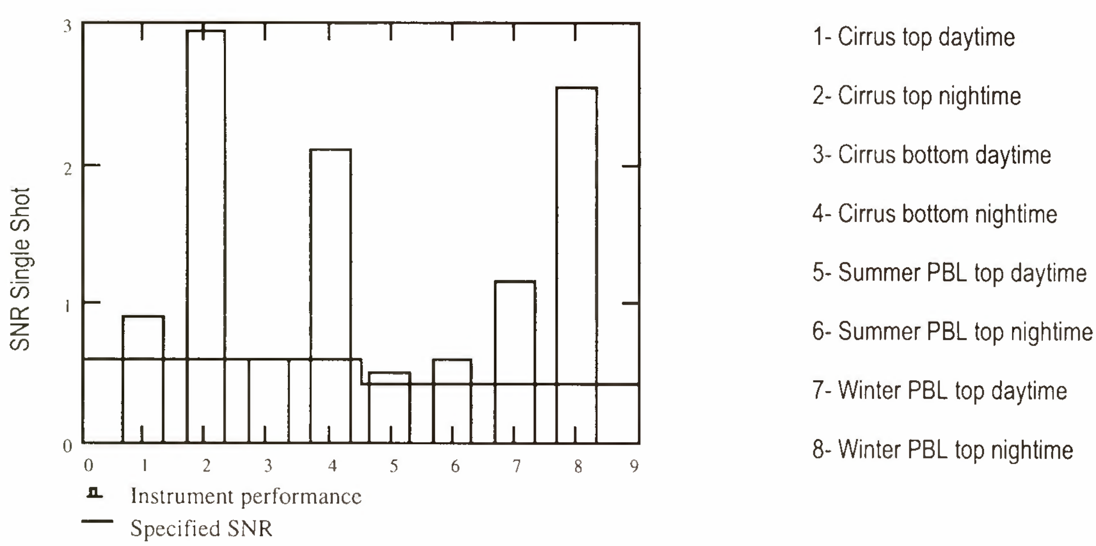

Figure 6.4. *ATLID Single Shot Performance*

Instrument Interfaces

The estimated instrument interface requirements are 240 kg, 500 W and a volume of 1.6 × 13 × 11 m^3; the data rate is 1.08 Mbps.

Instrument Development Status

ATLID has been studied for about a decade and was considered a candidate instrument for ENVISAT. At that time, it was not selected because of lack of technological maturity. Presently an industrial consortium is conducting a pre-development study of key technologies, which includes breadboarding of critical items, among others the laser head, its power supply and thermal control, the telescope, the optical filters and the detection chain as well as the scanning mechanism assembly. These activities have already demonstrated the validity of the ATLID concept and the maturity of the technologies to be applied.

In parallel with these technological activities, signal processing studies have been performed on various subjects like the inversion algorithms, the effect of multiple scattering and the detection and parameter estimation at low SNR.

6.1.3. Cloud Profiling Radar

Instrument Objectives

The objective of the Cloud Profiling Radar (CPR) is to provide vertical profiles of cloud structures along the satellite track. Such information is deduced from the measured radar backscatter signals from cloud particles. The unique feature of the CPR is its capability to emit microwave pulses to penetrate deep into lower cloud layers which cannot be viewed by passive optical sensors or reached by ATLID. Table 6.2 summarizes the specification of the CPR concept.

Figure 6.5 illustrates the measurement principle. The instrument is a fixed pointing millimeterwave radar with a narrow pencil beam. The pointing direction can be towards nadir or off-nadir (tilted forward or backward). Detailed trade-offs have not yet been performed so that the concept is preliminary.

Frequency	78 or 94 GHz
Polarisation	Linear (along or across-track)
Radar beam pointing	Fixed vertical (nadir) or tilted (backward or forward)
Vertical range	0.25 to 20 km or 25 km
Vertical resolution	250 to 500 m
Horizontal resolution (for 500 m vertical resolution)	0.7 km across-track and 1 km along-track for a sensitivity of -22 dBz
Cloud reflectivity factor dynamic range	-30 to +20 dBz
Max. range sidelobe level w.r.t peak power	-60 to -80 dB
Antenna aperture size	$\leq$ 2.5 m diameter
Beam foot-print size	0.7 to 0.84 km
Life time	$\geq$ 4 years

Table 6.2. *Cloud Profiling Radar Specification*

A number of comments apply to this specification:

1) Due to small cloud particle sizes, a short wavelength radar (3-3.8 mm) is preferable. Although the 78-79 GHz band is currently allocated to Earth Exploration satellites, the radar can have approximately 3 dB higher sensitivity at 94 GHz as compared to 78 GHz. Therefore, the choice of frequency is still open, pending on the approval of a request for a new frequency allocation at 94 GHz.

2) For horizontal resolution, the along-track integration length depends on the reflectivity of clouds.

3) A high range sidelobe ratio is required by the very high surface clutter level as compared to the average backscatter signal level. A worst case of +15 dB surface reflectivity has been assumed (sea surface at vertical incidence).

4) Cloud models identical to the ones used for the ATLID performance analysis are being applied to this instrument. Though, the ATLID models have been converted to microwave models which are more appropriate for the CPR analyses.

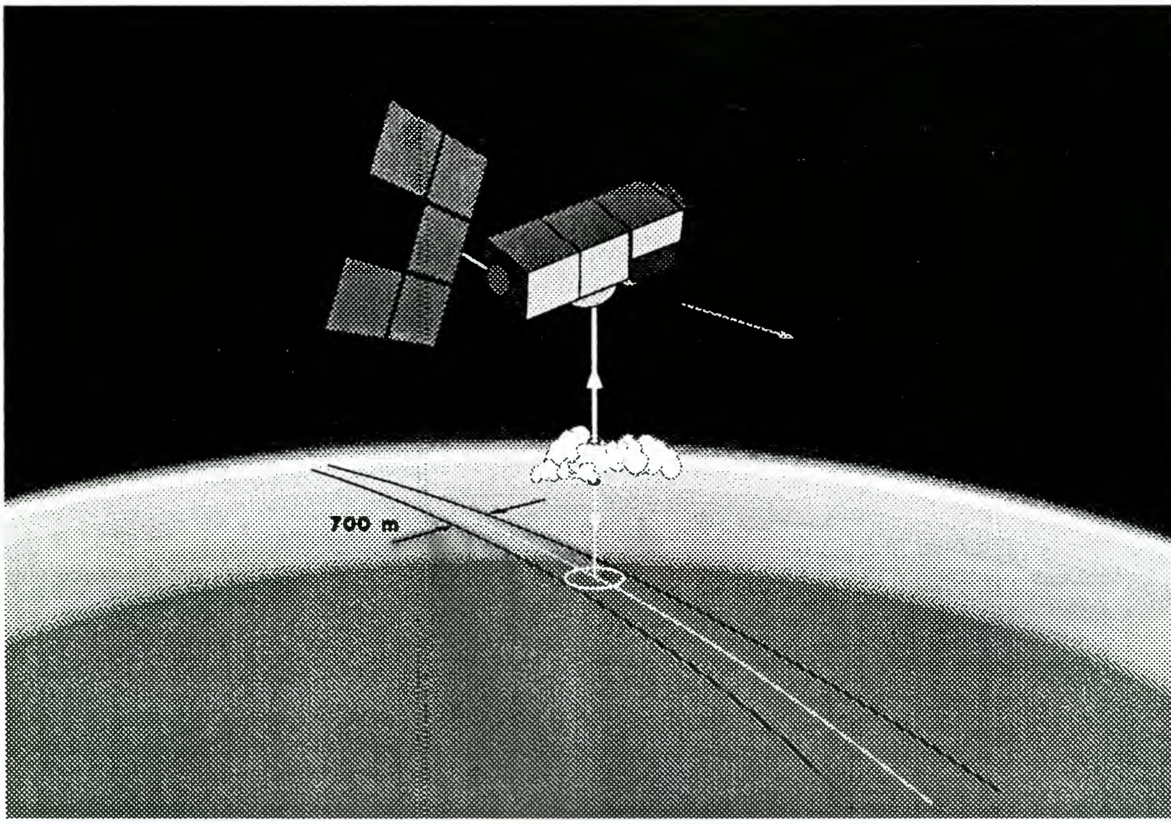

Figure 6.5. *CPR Measurement Principle*

Instrument Description

The instrument concept consists of the following subsystems:

- The digital electronics sub-system including the waveform generation and the signal/data processing unit.
- The radio frequency subsystem with the up- and down conversion chains, frequency generator, high power amplifier and the low noise amplifier.
- The antenna subsystem including the reflector and the feed waveguides/quasi-optical chain.

Two design options are presently being investigated:

- A short pulse, non-pulse-compression radar concept where high peak power (> 1 kW) is needed in order to achieve an acceptable signal-to-noise ratio. This option is more suitable for achieving the required -80 dB range sidelobe ratio at the expense of higher noise level due to a larger receiver bandwidth, which is necessary for controlling the temporal sidelobe.

– A long pulse, pulse-compression radar concept where a lower peak power (< 50 W) is needed. However, the required -80 dB range sidelobe ratio is not achievable (-60 dB has so far been demonstrated in critical breadboarding activities).

In both cases, the achievable signal-to-noise ratio for low reflectivity clouds is less than unity, requiring a long integration time for reliable signal detection, e.g. > 5 s for clouds with a radar reflectivity factor of -30 dBz. Due to this low signal-to-noise ratio, the scene background noise at the Earth's surface can be substantially higher than the radar backscatter signal from clouds. It is therefore necessary to estimate the scene brightness temperature and to subtract it from the total measured power, calling for accurate noise measurements. Due to the high pulse repetition frequency ($\geq$ 3 KHz) of the radar, no noise measurements can be performed between the pulses. Therefore a small percentage of the transmit pulses would be suppressed to create echo-free time intervals.

Interfaces

Since the design definition of the CPR is still in progress, only limited interface information is available. Estimated values would be a mass of 250 kg, a power requirement of the order of 300 W and a data rate which would be below 30 kbps.

Instrument Development Status

Two parallel pre-phase A level studies were initiated in January 1996, which will be completed by January 1997.

The high power amplifier requires substantial development effort as no space qualified tube exists for this frequency range. Technology assessment studies have been initiated for an extended interaction klystron, a travelling wave tube and the associated high voltage generation/distribution sub-system.

The high frequency circuitry which causes high losses and the required reflector surface accuracy of 30 μm rms also need close attention. The former problem can be resolved by incorporating so-called quasi-optical (or beam waveguide) signal paths within the radar frontend. For the latter carbon fibre composite technology is available to manufacture reflectors of this size with the necessary surface accuracy. Foldable reflector concepts are being studied to provide easier accommodation.

Breadboarding of a CPR up- and down-conversion chain has been started in 1995 in order to demonstrate the feasibility of meeting the -80 dB range sidelobe requirement. Concerning the low noise amplifier, a technology activity is in preparation.

6.1.4. Cloud Imager

Instrument Objectives

This instrument is required to provide images in the visible and infra-red bands in support of the active instruments and the broadband radiometer. In particular, scene and cloud type identification (cloud top temperature) are required to validate the data collected by the other instruments.

One possible solution to meet these requirements is a modified ATSR.

Instrument Description

ATSR-1 (ERS-1) has channels at 1.6, 3.7, 11 and 12 μm while visible channels at 0.555, 0.659 and 0.865 μm have been added for ATSR-2 (ERS-2). The instrument has been optimized for the accurate determination of sea surface temperature. Radiometric resolution is about 0.05 K in the thermal infra-red channels. When averaged over an area of 50 × 5 km^2, the absolute accuracy is better than 0.5 K. The visible channels exhibit a signal-to-noise ratio of at least 20 for 0.5% albedo scene.

The instrument uses a conical scan providing two optical paths for forward and nadir viewing. The instantaneous field-of-view is 1.3 mrad, equivalent to a pixel size of 780 m at nadir from an altitude of 600 km. The collecting optics consist of an off-axis paraboloid mirror with an aperture of 110 mm and elliptical mirrors relaying the beams to the thermal infra-red detectors while refractive lenses are used for the visible channels. Two black body targets within the instrument provide calibration in the infra-red channels in addition to a diffuser for the visible and near infra-red channels.

A Stirling-cycle cooler maintains a temperature of 80 K for the infra-red channels to achieve the required radiometric performance.

Instrument Interfaces

The resource requirements are about 100 W for power and 80 kg for mass. The accommodation of the radiator for the mechanical cooler is rather flexible as no direct view to deep space is required. Instead size and orientation can be traded off and the heat transported via heat pipes or cooling loops. The data rate is 625 kbps.

Instrument Development Status

In their present configuration none of the ATSR models meets the Earth Explorer Earth Radiation Mission requirements in terms of field-of-view geometry. As a minimum the scanning mechanism needs to be adapted to the different orbit altitude and extended to provide a (near) horizon-to-horizon view. Various options have been identified for this purpose including increasing the cone angle by inclining the scanning mirror or changing to a linear scan.

6.1.5. GNSS Receiver

The baseline receiver is the GRAS instrument as presently under development by the Agency. It would be used for guidance and navigation functions of the satellite.

The receiver can be supplemented by a directional antenna, mounted in the anti-flight direction for obtaining atmospheric profiles from measuring the signals received from occulting GPS and GLONASS satellites. This would contribute to the Earth Explorer Atmospheric Profiling Mission described elsewhere (ESA, 1996c).

6.2. Mission Profile

6.2.1. Orbit Definition

The orbit parameters are in the first instance defined by the observation requirements as specified in chapter 4. Constraints arise from operational requirements and satellite design in general.

A sun synchronous orbit has been selected as the baseline. This will provide near global coverage, within the inherent limits of this type of orbit.

The altitude of the orbit has been chosen as a compromise between the performance requirements of the active instruments, i.e. ATLID and CPR, and the sizing of the propulsion system to compensate for atmospheric drag as well as the onboard actuators to compensate external and internal torques. An altitude of 603 km should satisfy both requirements.

This orbit has a repeat cycle of 22 days or 14 + 19/22 revolutions per day. The resulting inclination is 97.8°.

The local time of the descending node (LTDN) is 1400 hrs as defined by the observation requirements.

6.2.2. Instrument Coverage

The CPR provides a nadir look only with a footprint of approximately 0.7 km, so coverage is also limited to the instrument's footprint. At 603 km the ATLID scan angle of +/- 20° results in a swath width of 470 km; the swath widths of ScaRaB and ATSR are 1584 km assuming a linear scan angle of +/- 50° also for the latter instrument.

The maximum scene revisit period at the Equator would be less than five days for ATLID and less than two days for ScaRaB and the cloud imager. Complete global coverage would be achieved within seven and four days respectively.

6.2.3. Communication Scenario

The total instrument data rate is 1.76 Mbps to which an overhead of 0.46 Mbps has been added for coding and formatting resulting in an overall data volume of 13 Gbit per orbit.

The communication scenario is based on the use of a single ground station which should be located at a latitude as high as possible in order to minimize the number of blind orbits. For a station such as Kiruna, 9 orbits of coverage with varying contact duration are interleaved with 5 consecutive orbits without any contact. Whilst this strategy avoids the use of other stations, it implies onboard data storage for five orbits. For a total blind time of 575 minutes this means an onboard data storage volume of approximately 80 Gbit.

It is not possible to downlink all these data during one pass with the presently available X-band link. Data transfer will have to be spread over several orbits. This requirement is well within the capabilities of the existing infrastructure, which allow a maximum downlink rate of 100 Mbps.

6.2.4. Geo-location

Requirements on guidance, navigation and control are derived from instrument data geo-location requirements. Most of the end products are the result of averaging over fields of 50 × 5 km^2 on a monthly basis. No stringent requirements have been assumed to exist for the absolute pointing accuracy.

A conventional attitude control system as flown on ERS-1/2 will provide a pointing error of 2.5 mrad in pitch equivalent to an along-track error of 1500 m; the figures for the roll axis are 3.13 mrad in roll or 1875 m. Combining both figures gives a total pointing error of 2400 m.

Co-registration between instruments has to be performed to tighter tolerances to ensure the synergy of their data, e.g. the image data have to be representative of the clouds viewed by the lidar and the radar. A requirement of 300 m has tentatively been stipulated for alignment of instrument footprints at nadir, which is equivalent to about half of the imager pixel size.

ATLID requires a vertical accuracy of 100 m for locating cloud layers, which can only be achieved with the aid of precise determination of orbit altitude and roll axis pointing. Whilst the first requirement can be readily met by a GNSS based navigation system, the second requirement will have to be satisfied by a star tracker forming part of the instrument itself.

Basic assumptions for the parameters affecting geo-location have been derived from ERS flight data. For a nadir look, the total error is approximately 2.4 mrad (1450 m) and 7 mrad (4200 m) at the edge of a +/- 50° scan; all data are at 95% confidence level.

6.2.5. Operation Modes

The GRACE payload concept is designed to work continuously throughout the mission. Nominally there are no changes envisaged in the operating modes other than instrument commissioning and calibration. It will be possible however to command other operation modes for example to cater for instrument contingencies.

Platform operations would be limited to routine monitoring and control functions, the onboard subsystems being designed for a maximum of autonomy.

6.2.6. Lifetime

The nominal mission duration has been defined as a minimum of 4 years, which meets the observational requirements.

Limitations in mission life have been identified for the active instruments, i.e. the ATLID laser and the CPR high power amplifier. The propellant supply has been sized for two years in addition to the nominal lifetime.

6.3. Spacecraft Design

6.3.1. General Constraints

The satellite configuration concept is in the first place constrained by the accommodation of the instruments which all require an unobstructed Earth view. In addition provisions have to be made for the dissipation of thermal energy into space. To this end also requirements for accommodation on the non-sunlit face of the satellite have to be met. A classical configuration, based on the existing SPOT/ERS bus concept, would satisfy these needs and at the same time reduce the development risks. However, the special accommodation requirements of ATLID (large radiator area) and CPR (large antenna dish) will inevitably lead to a mission specific payload carrier structure.

A further constraint arises from the available launcher(s) as the satellite configuration must be compatible with the volume offered by the fairing. Launch vehicle performance is of lesser concern as the orbit altitude is rather low. All launchers offering adequate payload bay volume are able to place GRACE into a 600 km orbit.

6.3.2. Configuration

A possible GRACE configuration is shown in figure 6.6.

This configuration is based on the SPOT/ERS satellite concept with independent service and payload modules. It has been successfully used already for the Agency's ERS and ENVISAT satellites and thus makes maximum use of their heritage.

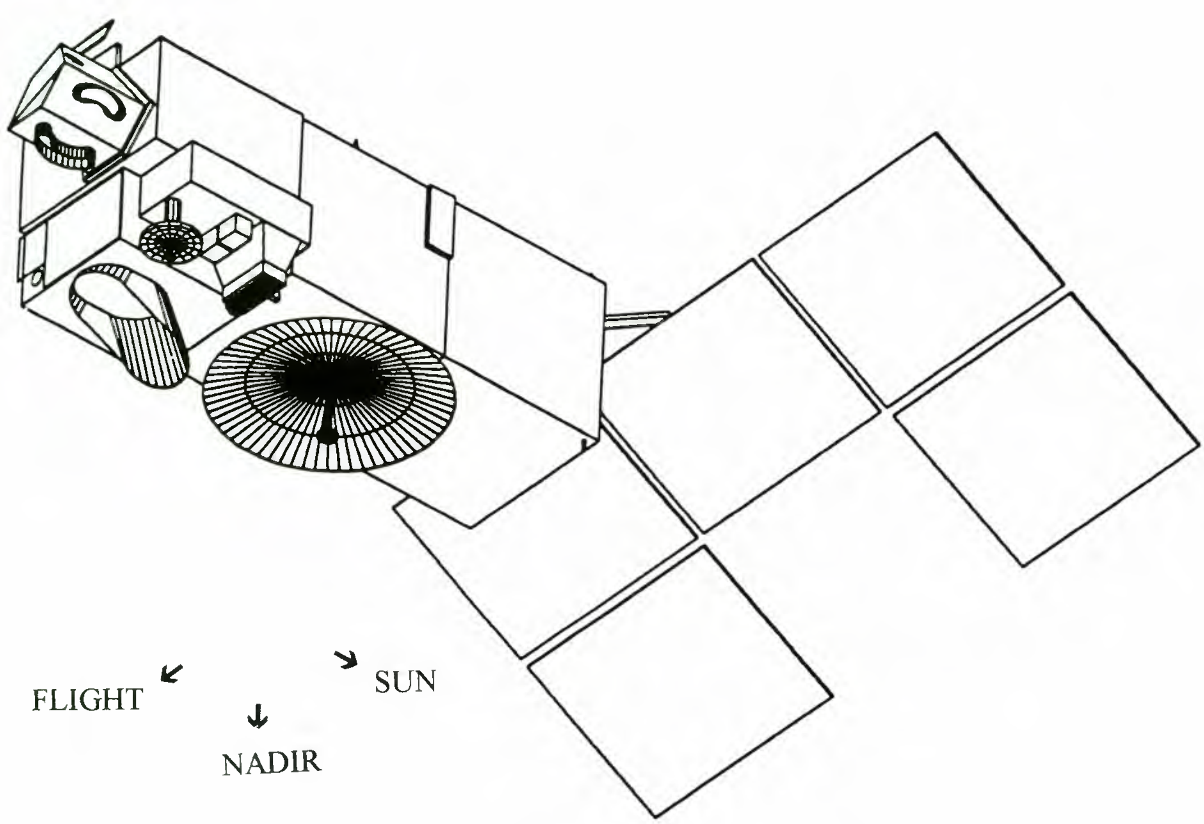

Figure 6.6. *Possible GRACE Configuration*

Instrument accommodation has not been optimized so far; the concept shown only demonstrates the feasibility of flying these instruments on an existing platform. Savings in structure mass and complexity could be achieved by means of combining structural elements of the instruments and the payload carrier, however at the expense of more complicated interface management. It should be noted in this context, that the ATLID configuration is based on ENVISAT design principles which require all instruments to be self supporting in order to simplify the interfaces. Likewise, the CPR antenna dish could be moved to the service module or at least protrude over the service module.

6.3.3. Structure and mechanisms

The structure concept derived from the general satellite configuration is based on a central cone which also establishes the interface to the launch vehicle. The equipments are mounted on panels which also form the outer part of the structure.

The equipments are pre-integrated on the panels for the sake of convenient access. Equipment requiring late access or service are mounted on special panels which can be readily removed. Large masses, like batteries or propellant tanks are mounted close to the central cylinder to reduce structural stresses.

There are no particularly stringent requirements on structure stiffness or mass, hence aluminium can be used. Should the need arise to reduce mass, carbon fibre reinforced plastic could substitute aluminium in critical areas.

There are no deployables foreseen other than the solar array and possibly the CPR antenna.

6.3.4. Thermal Control

Generally the thermal control subsystem could be a passive system, based on the selection of materials and surface properties to provide the necessary controlled heat flows. Heaters could be used for critical equipments requiring a rather narrow temperature range.

Equipment with high heat dissipation like the ATLID laser and the CPR high power amplifier would be equipped with radiators to dissipate heat. Heat pipes and/or two-phase cooling loops may have to be employed for the transmission of thermal energy from the sources to these radiators. Similar but much less stringent considerations apply to the accommodation of ATSR for the heat dissipation of the focal plane cooler.

Equipment accommodation on the outer panels needs to be optimised for thermal considerations. Heat input from solar irradiation, subject to change throughout the mission, can will be achieved by means of suitable selection of outer surface properties.

A preliminary assessment of heat loads has shown that thermal control can be maintained with a comfortable margin.

6.3.5. Propulsion

At the selected orbit altitude air drag is the main driver for the sizing of the propellant system. The residual atmosphere will cause the orbit to decay unless compensated by velocity increments generated onboard. This velocity change can be provided by a hydrazine propulsion system with a propellant mass of about 100 kg. This is well within the capability of the proposed platform in a 2-tank configuration, still providing sufficient margin to cater for launcher injection errors. Only in-plane manoeuvres are planned as no requirements exist for maintaining the LTDN to close tolerances requiring out-of-plane manoeuvres.

6.3.6. Attitude and Orbit Determination and Control

The requirements and assumptions for geo-localisation presented in section 6.2.4 can be satisfied by several concepts. Emphasis has been placed on a simple system in order to minimise complexity and to maximise the reuse of existing technology.

A classical attitude measurement system based on the SPOT/ERS bus heritage and using Earth and sun sensors and gyros will meet the requirements.

Reaction wheels of the SPOT MKII type provide a maximum torque of 0.45 Nm and a momentum of 45 Nms can compensate external and satellite induced disturbance torque and momentum. Reaction wheel desaturation needs to be performed at least once per orbit, for which a set of magnetotorquers is baselined.

Orbit determination can be readily performed by means of a GNSS based navigation system. This concept, making use of the GRAS instrument, will provide real time satellite position estimates with an accuracy of about 100 metres thereby eliminating a significant location error contribution. Orbit reconstitution would be performed on the basis of these measurements on ground.

6.3.7. Command and Data Management

In the satellite concept, a central computer controls all units via the Onboard Data Handling (OBDH) bus. Science data in packet format are directly fed from the instruments to the solid state mass memory. Such memories have been developed for ongoing space missions already; developments towards larger storage capacities are in progress. This design concept is very flexible by virtue of its modular design. Although originally intended as a replacement of mechanical tape recorders, it can support also advanced data handling functions like signal compression and encoding. Simultaneous access for data storage and retrieval is possible.

The central computer manages the onboard data flow, the communications to and from ground and performs the attitude and orbit control data processing.

The Agency's packet telemetry and command standard will be the baseline for satellite control.

6.3.8. Communications

The communication system concept consists of two parts: the S-band TT/C part for the transmission of housekeeping data and reception of telecommands and the X-band part for the transmission of instrument and housekeeping data. Off the shelf equipment could meet these requirements.

6.3.9. Power Generation and Energy Storage

The definition of the power and energy system concept depends in the first instance on the bus power level. The topology used so far is the unregulated bus type implemented in ERS and ENVISAT.

For a bus power level of approximately 1600 W the solar array must be sized for 2800 W to account for battery charging. This leads to a solar array area of about 20 m^2 on the basis of high efficiency solar cells.

Electrical energy is stored in a set of batteries to power the satellite during eclipses. A configuration of 3 NiCd batteries providing 40 Ah each is adequate.

6.3.10. Resource Budgets

The mass and power budgets are given in table 6.3.

These data have been derived from existing hardware, scaling them to the specific requirements of this mission as applicable.

Significant margin allocations have been made reflecting the development status.

	Mass		Power	
Service Module		790 kg		360 W
Payload Module		1081 kg		1155 W
Instruments	646 kg		945 W	
Payload Carrier	435 kg		210 W	
Propellant		150 kg		
Margin (not on propellant)		479 kg		85 W
Total		2500 kg		1600 W

Table 6.3. *GRACE Resource Budgets*

6.4. Launcher

Two scenarios have been evaluated for the selection of a launch vehicle:

- launch shared with another mission
- dedicated launch.

For both cases volume available in the payload bay is the main constraint rather than vehicle performance.

If a launch is to be shared, only the European AR5 and the Japanese H2 launchers offer the necessary volume and performance. It has to be noted in this context that accepting a partner mission for GRACE would impose rather severe constraints on both as potentially conflicting orbit requirements must be accommodated.

For a dedicated launch again only the AR5 and H2 vehicles are suitable because of the available fairing volume.

6.5. Ground Segment

6.5.1. General

From the ground segment point of view this mission is characterised by a relatively high aggregate instrument data rate, the presence of multiple instruments and the absence of a requirement for the supply of (near-) real time data products. A classical ground segment concept as depicted in figure 6.7 would meet the operational requirements.

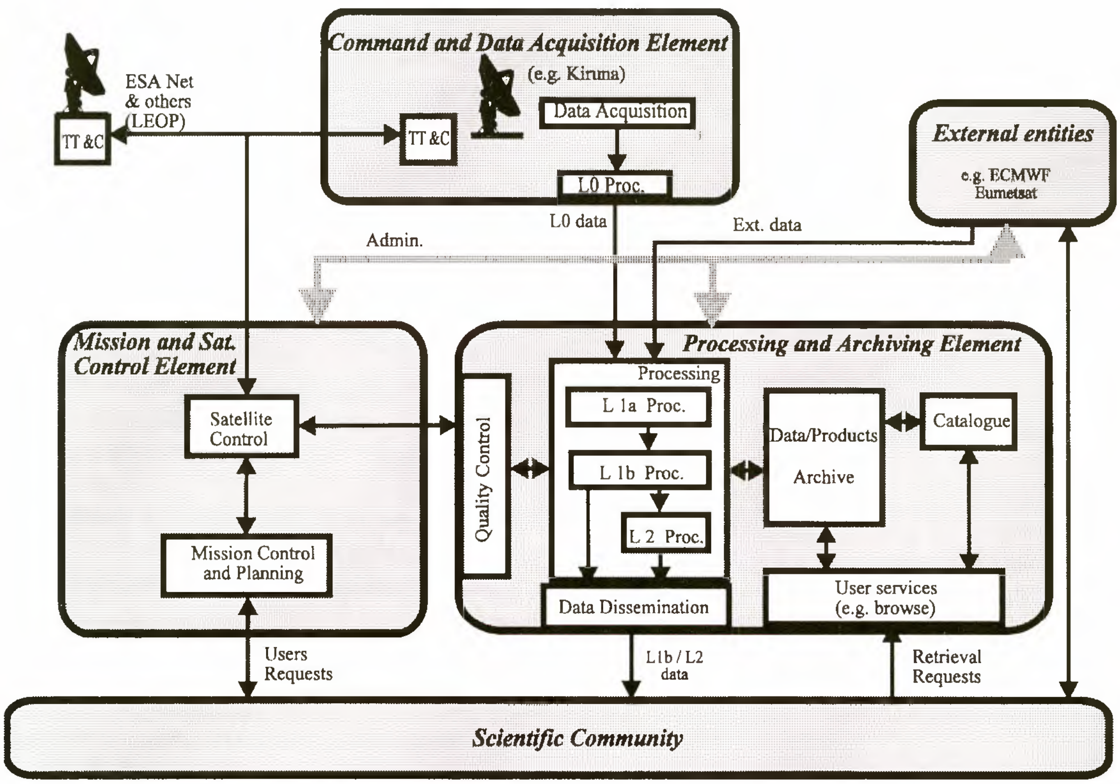

Figure 6.7. *Ground Segment Blockdiagram*

It includes three main elements: the Command and Data Acquisition Element, the Mission and Satellite Control Element and the Processing and Archiving Element.

Reuse of existing facilities should be planned to the extent possible in order to minimize cost.

6.5.2. Command and Data Acquisition

A single ground station, located in Northern Europe, e.g. Kiruna, is baselined for satellite command and data acquisition. The station also performs data processing to level 0 and provides short term data storage (~ 1 week).

The Agency's ground station network (ESTRACK) is baselined for the support of telemetry acquisition, tracking measurements and commanding (TT/C). It is used for the launch and early orbit phases of the mission as well as for routine operations.

The S-band ground station used for satellite monitoring and control may be co-located with the mission control centre or the X-band ground station if longer contact periods should be required for certain mission phases.

6.5.3. Mission and Satellite Control

The Mission and Satellite Control Element will also be responsible for the monitoring and control of the ground segment as well as the availability of external data. The communication requirements are well within the capabilities developed for other missions.

Interaction between spacecraft and ground segment will be minimised by providing a maximum of autonomy in the design of the space segment.

6.5.4. Processing and Archiving Element

After data acquisition by the ground station, the Processing and Archive Element would perform first level data processing up to level 1b, i.e. calibrated, Earth located and quality controlled data together with associated auxiliary data and archiving. A single interface would be provided to the scientific community which would generate the higher level data products. Also acquisition and processing of data from other sources would be performed for the generation of ERM products.

6.5.5. Data Products

The level of data to be produced are the following:

- Level 0 – raw payload data as telemetered from the satellite.
- Level 1a – 'de-packetised' data, sorted in files with calibration data attached but no correction performed.
- Level 1b – calibrated and corrected.

Data archiving would be done at level 1a. It can be assumed that the data volume will be in the same range as the raw data. This will produce a volume of 64 Tbits per year of level 1a data. Archived data would be available for delivery on request for the duration of the mission.

6.5.6. Data Processing Algorithms

Data processing algorithms exist for all instruments which have been flown already. They will need to be adapted to the specific needs of this mission. Some lidar algorithms have already been developed and need further optimisation. The cloud radar algorithms yet have to be developed but will be based on those used for ground based instruments and the rain radar.

Emphasis will be placed on the development of algorithms covering more than one instrument in order to make best use of their synergy. Relevant experience already exists inter alia for the broadband radiometer, the cloud imager and sounding instruments. Processing and amalgamation of data derived from other missions will have to be developed for the Earth Explorer Earth Radiation Mission.

6.6. Options

The ATLID design and breadboarding activities have shown that the present concept is feasible and does not contain risk beyond the level of normal development work. In the event of difficulties arising during the detailed design phase the instrument could be readily changed to a non-scanning lidar.

This would result in a higher shot density for the given size of the resolution cell as the laser repetition rate would provide contiguous footprints.This could be used for a reduction of the pulse energy or a decrease in repetition rate, which should increase laser reliability and life time.

Changing to a fixed lidar concept does not only entail the deletion of the scanning mechanism itself but also the compensating flywheel and its control system as well as the lag angle compensator and the star tracker. This could have significant cost implications. Furthermore the design of the telescope could be simplified as lightweight techniques would not need to be used.

In the event of flying a non-scanning lidar, the requirements for the other instruments should be also reviewed. The synergy with a limited swath or even non-scanning radiometer and an unmodified ATSR should be investigated.

For the broadband radiometer and the imager other instruments are available internationally, which would meet the Earth Explorer Earth Radiation Mission requirements without design change, like CERES and AVHRR

7. Programmatics

7.1. General

The Earth Radiation Mission would be implemented as an Earth Explorer Programme of research missions if selected after phase A studies carried out within the frame of the Agency's Earth Observation Preparatory Programme.

7.2. Critical Areas and Open Issues

ATLID is an advanced instrument. It has been subject to a long and rigorous technology development effort which included breadboarding and testing of the critical elements. This technology effort is continuing. The potential problems are known and there is confidence that the development can be completed in good time. A potential simplification is the elimination of the scanning. This simplification requires further analysis to assess the impact on the mission return.

The Cloud Radar is conceptually simple and though space hardware at 94 GHz is a novelty, development effort started some years ago and there is confidence in its successful completion. The issue of frequency allocation at 94 Ghz is still open (78 Ghz would still be a back-up).

There are suitable candidates for the Cloud Imager (ATSR) and Broadband Radiometer (ScaRaB) which have already flown. No critical areas are identified.

At overall satellite level this mission is in the ERS/SPOT class with the known implications on development effort. The ground segment will have demanding constraints as usual in multi instrument missions but will lie within the capabilities developed for ERS and ENVISAT. The assimilation of data from the core mission and from the auxiliary elements, mainly meteorological observations, will require an important effort in the development of processing algorithms.

In summary, this is a classical project with significant effort required at instrument, system development and integration level.

7.3. Related Missions and Timeliness

Several present and planned missions are related to the Earth Explorer Earth Radiation Mission. The NASA missions EOS AM-1 and PM-1 have as objectives better observations of clouds, aerosols and radiation balance. The Japanese ADEOS series (from 1996) with the

French experiment POLDER and the joint NASA-NASDA mission TRMM focused on precipitation would also contribute data to the study of Earth radiation. From Europe the ERS and ENVISAT missions will contribute mainly with (A)ATSR and the chemistry instruments.

A reflight of ScaRaB is planned to take place in 1997 on a Russian RESSURS satellite. The geostationary and polar meteorological satellites will provide essential data for this mission. GERB on MSG has to be mentioned for its dedicated radiation balance objectives. The TRMM (1997) and the ATMOS-A1 (2003) missions focus on precipitation but include observations related to the Earth Explorer Earth Radiation Mission.

However, none of these missions will supply the data required to address the requirements of the Earth Explorer Earth Radiation Mission. The need for this mission has been recognised by other space agencies. Here, specific reference can be made to NASDA's ATMOS B 1 (2005) which includes a Cloud Radar (CPR), a lidar (L-ALT-1), two broadband radiometers (ERBE and CERES) and an Imager (IMG-2) probably in a mid inclination drifting orbit. There is also interest in the US for such a mission.

Possible coordination with the proposed Japanese ATMOS B 1 provides a reason for considering an early implementation of the Earth Explorer Earth Radiation Mission. It is also pertinent to note that this is one of the priority missions considered by GEWEX.

7.4. International Cooperation

It is clear that the Earth Explorer Earth Radiation Mission is of universal interest and has ambitious objectives which offer a wide range of possibilities for cooperation. The exploitation of the data from this Explorer and from the related missions is a global task that requires international cooperation for the exchange of data and results and for the joint elaboration of models.

7.5. Enhancement of European Capabilities and Applications Potential

Immediate applications include the better exploitation of data from geostationary and polar imagers and sounders of current and planned operational systems as the knowledge of clouds will be substantially improved. In this sense, the Earth Explorer Earth Radiation Mission responds to some of the recommendations of the WMO concerning requirements for future meteorological operational systems. The modelling activities required to support this mission will improve GCMs and other models.

The ATLID and Cloud Radar developments have not only potential application in monitoring systems as such, but the technology and hardware developed can be used for other purposes, e.g. beam limited altimetry, laser or microwave, which have also operational applications. The Cloud Imager could also be a precursor for advanced operational imagers.

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List of Acronyms

ADEOS	Advanced Earth Observing Satellite
ARM	Atmospheric Radiation Measurement
ARMA	ATLID Reference Model of the Atmosphere
ATLID	Atmospheric Lidar
ATSR	Along Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
CERES	Clouds and the Earth's Radiant Energy System
CPR	Cloud Profiling Radar
CRF	Cloud Radiative Forcing
ECLIPS	Experimental Cloud Lidar Pilot Study
ENSO	El Niño Southern Oscillation
ENVISAT	Environmental satellite
ERB	Earth Radiation Budget
ERBE	ERB Experiment
ERBS	ERB Satellite
ERM	Earth Radiation Mission
ERS	Earth Resources Satellite
GCM	General Circulation Model
GERB	Geostationary ERB Experiment
GEWEX	Global Energy and Water Experiment
GLONASS	Global Navigation Satellite System
GMS	Geostationary Meteorological Satellite
GNSS	Global Navigation Satellite System
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning Satellite
GRACE	Global Radiation, Aerosol and Cloud Explorer
GRAS	GPS/GLONASS Receiver for Atmospheric Sounding
ICSU	International Council of Scientific Unions
INSAT	Indian Satellite
IR	Infrared
IRIS	IR Interferometer Spectrometer
ISCCP	International Satellite Cloud Climatology Project
IWC	Ice Water Content

LTDN	Local Time of the Descending Node
LW	Longwave
LWC	Liquid Water Content
METOP	Operational Meterological Satellite
MSG	Meteosat Second Generation
MTPE	Mission to Planet Earth
NASA	National Aeronautics And Space Administration
OBDH	On Board Data Handling
OLR	Outgoing LW Radiation
PBL	Planetary Boundary Layer
POLDER	Polarization and Directionality of Earth Reflectances
ScaRaB	Scanner for Radiation Budget
SEVIRI	Scanning Enhanced VIS IR Imager
SNR	Signal to Noise Ratio
SPOT	Satellite Probatoire de l'Observation de la Terre
SRB	Surface Radiation Budget
SW	Shortwave
TOA	Top of the Atmosphere
TRMM	Tropical Rainfall Measuring Mission
TT/C	Telemetry, Tracking and Commands
UARS	Upper Atmosphere Research Satellite
UNEP	United Nations Environmental Programme
VIS	Visible
WMO	World Meteorological Organisation

Appendix

Definition of Radiation Terms

Albedo: the ratio (often expressed as a percentage) of reflected shortwave to incident solar irradiance, either at the top of the atmosphere (planetary albedo) or at the surface (surface albedo). Planetary albedo depends on the solar zenith angle as well as on scene properties. Surface albedo depends on the angular distribution of the solar radiation incident on the surface (direct beam and diffuse radiation) as well as on surface properties.

Atmospheric window: the spectral domain extending roughly from 8 to 13 μm (with the exception of the ozone band at 9.6 μm) in which absorption of radiation by the clear atmosphere is relatively weak, except in warm, humid atmospheres due to the water vapour continuum.

Bidirectional reflectance distribution function (BDRF): the ratio of the radiance reflected in a given direction to the radiance that would be reflected under the same conditions of illumination by a Lambertian (i.e. an isotropic) reflector having the same albedo as the observed scene.

Flux, or Irradiance: The radiant energy per unit area, per unit wavelength or wavenumber, integrated over a hemisphere (2π steradian), in an upward or downward direction.

Radiance or intensity: The radiant energy per unit area, per unit wavelength (or wavenumber), per unit solid angle, at a given angle to the vertical .

Wavelength (usual units m), wavenumber, $\nu = 1 / \lambda$ (usual units cm^{-1}), and frequency f (usual units Hz), are related by $c = f\lambda = f / \nu$.

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