THE EARTH RADIATION MISSION : THE ROLE OF CLOUDS AND AEROSOLS

J.P.V. Poiares Baptista, A. Culoma, P. Ingmann, W. Leibrandt, C.-C. Lin and R. Meynart
European Space Agency - ESTEC, Po Box 299, 2200 AG Noordwijk, The Netherlands
Tel.: +31-71-565-4319, Fax: +31-565-71-565-5675, e-mail:

ABSTRACT

The Earth Radiation Mission (ERM) was one of four candidate Core Earth Explorers under the 'ESA Living Planet Programme' [ESA SP-1227, 1998]. The payload comprised a Cloud-Profiling-Radar (CPR), a backscatter lidar (ATLID), a multi-spectral imager (MSI) and a broad-band radiometer (BBR).

Discussions between the Japanese and European scientific communities have lead to the definition of joint scientific objectives.

In this paper the scientific requirements and the consequent mission engineering requirements are discussed.

While the ERM has not been selected as one of the next Core Earth Explorers, the Earth Science Advisory of the European Space Agency has recommended that this mission is pursued as a joint Japanese-European effort.

The objective of this paper is to present an extensive summary of the Earth Radiation Mission Report for Assessment. [ESA SP-1233(3), 1999]

ERM SCIENCE OBJECTIVES

The ERM has been specifically defined with the scientific objective of determining world wide the vertical profiles of cloud and aerosol field characteristics to provide basic (and essential) input data for numerical modelling and studies (on a global scale) of:

- the divergence of radiative energy,
- aerosol-cloud-radiation interaction,
- the vertical distribution of water and ice and their transport by clouds
- the vertical cloud field overlap and cloud-precipitation interactions

These objectives were jointly defined by Japanese and European scientific communities.

The cloud and aerosol data available at present is of limited value to provide validation for atmospheric models. In these models the major uncertainty is the representation of clouds and aerosols. Traditionally, cloud parameterization schemes in numerical models have been validated by comparing long runs of such models with the climatological observations of fluxes. Such validations are in fact rather crude since for a given flux at the Top-Of-the Atmosphere (TOA) there is more than one possible solution.

The ERM addresses this issue by using a so called snapshot approach. This consists in measuring the vertical profiles of clouds and aerosols (using a nadir looking radar and lidar) and the constraining TOA radiance (using a broad-band-radiometer). To understand the wider context of the measurements an imager is used.

The mission supports the goals of the World Climate Research Programme (WCRP) and, in particular, of its sub-programme Global Energy and Water Experiment (GEWEX) which is intended to develop an improved understanding of energy and water fluxes within the climate system, to secure reliable forecasts of weather and climate.

In order to meet ERM's objectives, observations are required on a global scale of :

- Cloud boundaries (top and base), even of multilayer clouds, and consequently height-resolved fractional cloud cover
- Vertical profiles of ice water content and ice particle size
- Vertical profiles of liquid water content
- Detection of precipitation and estimation of light precipitation
- Detection of aerosol layers and estimates of their optical depth
- Short-wave (SW) and long-wave (LW) radiances at the top-of-the-atmosphere.

OBSERVATIONAL REQUIREMENTS

The entire mission observational requirements (including instrument requirements) were derived to achieve a TOA flux accuracy of 10 Wm^{-2} on a synoptic scale. The sensitivity limits and accuracy required for the key geo-physical parameters are listed in Table 1. These have lead also to the definition of the instrument requirements that are used later in this paper.

Parameter	Detectability	Accuracy
Fractional Cloud Cover	5 %	5 %
Cloud Top/Base - Ice - Liquid	N/A N/A	500 m 300 m
Ice Water Content	0.001 g m^{-3}	+40 / -30 %
Ice Effective Radius	N/A	+40 / -30 %
Liquid Water Content (and effective radius)	Optical depth 1	+100% / -50%
Aerosol Optical Depth	0.04	10 %
SW/LW Radiances, TOA	N/A	1.5 Wm^{-2} sr^{-1}

Table 1 : Accuracy of the Observations Required

The scientific objectives can only be met with co-located and simultaneous measurements of the two active sounders with other complementary instrumentation onboard the same satellite. The radar and lidar footprints need to be co-located to better than 500 m to be able to use both active instruments in synergy to retrieve cloud properties within the required accuracy.

Due to the snapshot approach used the radar and the lidar are required to make observations in only rather narrow fields of view about nadir, with footprint dimensions of under 200 m and 1 km respectively. This limits the ERM complexity and cost.

By contrast, the multi-spectral imager and the broadband radiometer have a relatively small impact on the overall costs of the mission. The multi-spectral imager enables clear distinction to be made between different cloud types. The data of the broadband radiometer provides values of the radiance at the top of the atmosphere (TOA) and thus the constraining value for the estimates of the vertical radiative flux divergence profiles within the atmosphere.

The passive instruments need to have larger swaths in the across-track direction than the active instruments. As the typical correlation length of cloud structures sometimes extends beyond the size of the reference cells, the swaths of the multi-spectral imager and broadband radiometer have been specified at a width of 100 km approximately.

Regarding the orbit requirements a nearly polar orbit ensures that all climate zones will be sampled. An orbit with an equatorial crossing will ensure a maximal signal in reflected solar radiation for both passive sensors. A preceding orbit is not strictly necessary for the ERM due to the snapshot approach used.

The mission objectives can be met with a minimum life of two years.

SUMMARY OF OVERALL ERM CONCEPT

After extensive trade-offs and optimisation, a sun-synchronous orbit with an altitude of about 370 km was selected. This is low enough to ensure good performance with active instruments of reasonable size, but not so low that aerodynamic drag effects are excessive. The node crossing time is 1300 hr and the recommended orbit has a 3 day repeat cycle. This repeat coverage within the 50 km reference dimension requires orbit altitude maintenance manoeuvres to control the period and hence the longitude of the ascending or descending node.

In the recommended concept the platform includes all support functions (power; data acquisition, formatting and transmission to ground; attitude and orbit control, etc) as well as the mechanical structure and thermal control.

This integrated architecture, in which there is no equivalent of the dedicated payload equipment bay which is a feature of ERS, METOP and other large E.O. spacecraft, offers the minimum mass and is the most cost-effective solution for ERM spacecraft.

Rockot has been selected as the baseline launch vehicle because of its low cost, with Athena-II and PSLV as back-ups. The CPR antenna diameter of about 2 m has been selected to just fit in the Rockot fairing envelope and thus make optimum use of the available volume.

The ground segment is based to the maximum extent possible on the reuse of the Agency's existing infrastructure ; only a few upgrades will be required. Data processing will be limited to level 1 completed with archiving & dissemination capabilities (see "Ground Segment" later), all science data processing falling under the responsibility of the end users. No stringent requirements have been identified so far for the data delivery within a specified length of time to the end users but the system is able to provide fast access to the data.

ERM PAYLOAD

The definition of the ERM payload responds to the science requirements which have been elaborated earlier in this paper :

- The lidar operates in the near IR at a wavelength of 1.06 μm with a short pulse length so that profiles can be provided with a vertical resolution of 100 m and a vertical localisation of 100 m. The instrument will have sufficient sensitivity to detect a volume backscatter of 8.0 10^{-7} m^{-1} sr^{-1} for an integration length of 10 km and a signal-tonoise ratio of 2 during the day. At night the sensitivity is twice as good.

- The radar operates at 94 GHz with a pulse length of 3.3 μs in the nominal mode and 2.3 μs in the secondary mode so that a range resolution of 500 m is achieved in the former and 350 m in the latter. The radar footprint is about 700 m and, with an along track integration distance of 10 km, the sensitivity will be –34.4 dBZ for clouds at 1 km altitude in the tropics and –36.8 dBZ for ice clouds (at 8 km) for a radiometric accuracy of 1.7 dB. For 1 km integration length the sensitivity is degraded by 5 dB.
- The multi-spectral imager has a pixel size of 1 km and provide images over a swath of about 100 km around nadir in the spectral bands: 0.65, 0.87, 1.6, 8.7, 10.8 and 11.8 μm. These data will provide a context in which to gauge the representativeness of the much narrower field profiling data provided by the active instruments, together with the ability to derive cloud products in the same manner as used for a conventional passive imager.
- The broadband radiometer instrument provides measurements of the short wave 0.2 to 4.0 μm and long-wave 4.0 to 50 μm radiance at the top of the atmosphere. The swath will be at least 100 km with an instantaneous field of view of 50 x 50 km^2 and a sampling distance of 30 km.

Whilst the active instruments are novel, in the sense that relatively little flight experience is available from other missions at the time of writing, the passive instruments are based to a significant extent on the heritage provided by other similar instruments.

The instrument characteristics have been optimised for ERM to ensure on the one hand a maximum of synergy and on the other to arrive at a design which is as simple as possible. For the lidar, the low orbit altitude has resulted in reduced laser pulse energy, leading to lower mass, power and thermal dissipation requirements. For the imager and the BBR, changing from the traditional horizon-to-horizon field of view to a narrow swath has allowed simple instrument design concepts to be used. Their compact designs are also less demanding regarding accommodation on the platform despite critical field of view requirements.

The design of the instruments and their performance parameters are presented in the following sections. A summary of their overall resource demands appears in Table 2. The mass and power figures include contingency (20 % extra on basic mass estimates and 15 % on power).

Instrument	Mass, kg	Power, W	Data, kbps
ATLID	226*	210	400
CPR	134	273	30
CI	15	45	50
BBR	7	23	3
Totals	**382 kg**	**551 W**	**~ 500 kbps**

** Includes ~ 50 kg structure mass to support CPR*

Table 2 : ERM Payload Resources

ATLID

Pre-development activities relevant to ATLID have been funded by ESA for more than 10 years during which critical elements have all been successfully breadboarded. The instrument is organised around the various functions illustrated in Figure 1.

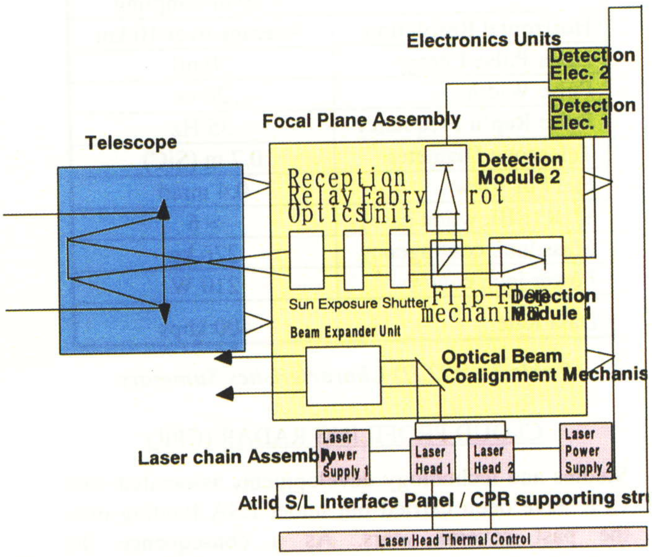

Figure 1 : ATLID Functional Diagram

In earlier studies a cross-track scanning capability was included which required a dynamic co-alignment device and a star sensor ; these are no longer necessary for a fixed nadir-looking configuration. The transmitter function includes the laser head itself, its thermal control unit and the laser power supply. The baseline laser is a diode-pumped Nd-YAG head emitting at 1.06 μm wavelength. An emission redundancy block allows either of the two transmitter chains to be used. A beam co-alignment device may also be included between the transmission and reception paths if this finally proves to be necessary.

The opto-mechanical assembly comprises the receiver telescope, and the focal plane assembly within which are mounted the reception relay optics and a narrowband Fabry Perot filter for daylight background reduction. The redundant detection modules use avalanche photodiode detectors and associated detection electronics.

The overall instrument thermal control is based on conventional hardware (radiators, MLI, paint, heaters). A dedicated system based on a two-phase fluid loop system is used for the laser head thermal control to evacuate heat load and stabilise the temperature of the pump-diodes.

Table 3 summarises the main characteristics of the current design of ATLID :

Parameter	Value
Wavelength	1.06 µm Nd-YAG
Vertical Range	0 - 30 km
Vertical Localisation	100 m
Vertical Resolution	< 100 m (pulse width); < 50 m sampling
Horizontal Resolution	Average over 10 km
Laser Pulse Energy	70 mJ
Pulse Width	20 ns
Pulse Rep'n Frequency	35 Hz
Telescope Diameter	0.7 m (SiC)
Field of View	0.4 mrad
SNR (PBL worst case)	> 6
Mass incl. contingency	226 kg
Power incl. cont'y	210 W
Data Rate	400 kbps

Table 3 : ATLID Characteristics Summary

CLOUD PROFILING RADAR (CPR)

Studies and technology developments associated with CPR have been carried out under ESA funding over the past several years. As a consequence the technology needed for the CPR is relatively mature and there are only a few fields where further development or verification is needed.

A functional block diagram of CPR is shown in Figure 2. For a more detailed description of CPR see elsewhere in this proceedings.

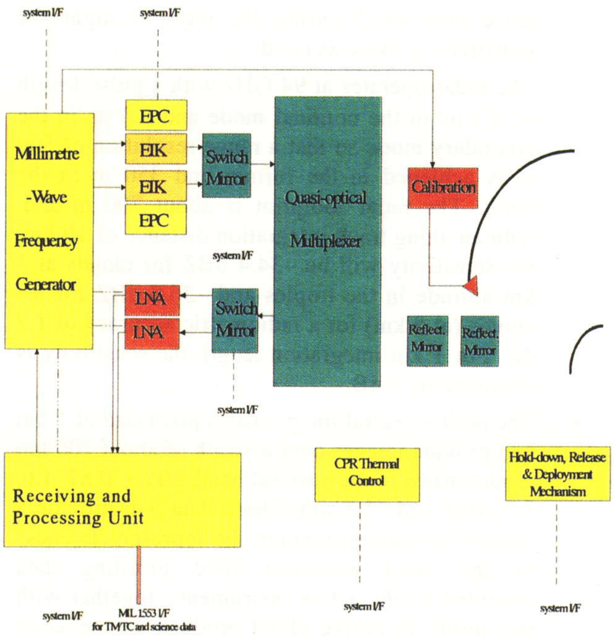

Figure 2 : CPR Block Diagram

The following general design features have been identified as the best compromise:

- Use of unmodulated CW pulses, as opposed to pulse compression techniques which compare unfavourably with respect to ground clutter performance ;
- Use of quasi-optical Tx/Rx multiplexing, as opposed to a solution with waveguide components which is unfavourable in terms of losses and hence system sensitivity ;
- Use of a deployed offset-Cassegrain antenna, as opposed to a fixed centre-fed dish on the satellite nadir plane (unfavourable in terms of sidelobe and accommodation considerations) ;
- Use of a passively cooled receiver front end, as a result of complexity/performance trade-offs ;
- Use of Extended Interaction Klystron (EIK) tube amplifiers for the transmit pulse, as a result of trade-offs between TWT and EIK tubes where the latter offer better performance with respect to peak power and efficiency and can be used at lower supply voltages while the TWT offers a longer lifetime ;
- Use of Digital Signal Processing for bandwidth determining filters and for detection.

In a similar way to ATLID :

- Earlier studies and bread-boarding activities have resolved several key design aspects for the CPR instrument, notably the choice of a single operating frequency at 94 GHz with high peak power, unmodulated transmitted pulses and a nadir-looking geometry ;
- Recommended design parameters from these earlier studies have been re-assessed, using performance evaluation software for the latest revisions to the requirements;
- Reductions in altitude and lifetime provide opportunities for reducing transmitter power and/or receiver diameter which, in turn, make thermal control easier, reduce instrument mass and power and improve lifetime/reliability.

Table 4 summarises the main characteristics of the current design of CPR :

Parameter	Value
Frequency	94 GHz
View Direction	Nadir only
Footprint	< 1000 m
Vertical Range	0.5 - 20 km
Vertical Localisation	100 m
Vertical Resolution	< 350 m
Horizontal Resolution	1 km
Transmitter Peak Power	1.5 kW
Pulse Repetition	~ 6000 Hz
Antenna Diameter	2.1 m (max)
Zmin	- 33 dBz
Mass incl. contingency	134 kg
Power incl. contingency	273 W
Data Rate	30 kbps

Table 4 : Main Characteristics of CPR

MULTI-SPECTRAL IMAGER

The recently-developed technology of uncooled microbolometer detector arrays was identified as the most promising approach for designing an instrument which is both affordable and easy to accommodate on the ERM platform. It offers significant advantages over rival concepts, notably for instrument size, mass and power which are all significantly lower than any of the other approaches.

The main instrument characteristics are:

- Mass 15 kg including 20 % contingency
- Power 46 W including 15 % contingency
- Dimensions 528 x 260 x 410 mm
- Data Rate Approx. 50 kbps

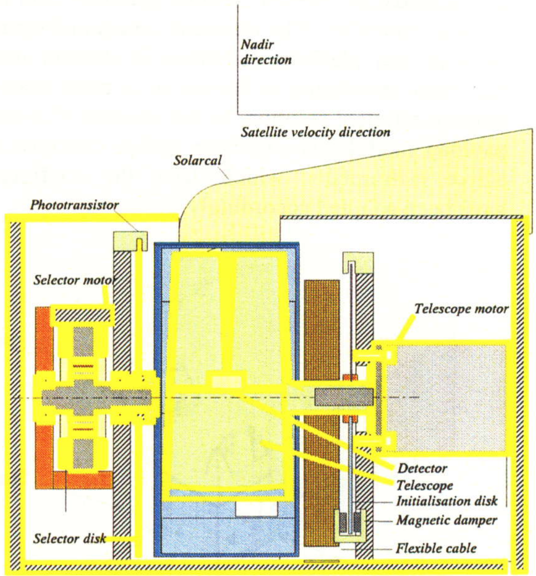

Figure 3 : Overview of BBR Concept

BROADBAND RADIOMETER (BBR)

For the BBR a purpose-built solution strictly matched to ERM needs using either :

- a simplified scanner, based on AATSR heritage for example ;
- a new small scanner concept defined by REOSC in a recent study contract for ESA ;
- a Combined Radiometer concept using a conical-scan AATSR-derived instrument to fulfil both the BBR and the CI functions.

The preferred solution (Figure 3) is the new compact, lightweight design concept described by REOSC since it meets the BBR requirements and ERM system constraints in an optimum manner.

The main instrument characteristics are :

Mass	7 kg including 20 % contingency
Power	23 W including 15 % contingency
Dimensions:	Optical Head 180 x 150 x 170 mm
Electronics:	200 x 300 x 50 mm
Data Rate	3 kbps

SATELLITE CONFIGURATION

The chosen satellite configuration shown in Figure 4 is the result of trade-offs between instrument accommodation, service module geometry and launch vehicle capability. The classical concept of separating payload and platform functions in distinct modules has been abandoned in favour of a more mass- and volume-efficient solution. In the absence of a classical payload module the structure design concepts of the active instruments, which drive the configuration, have been adapted accordingly.

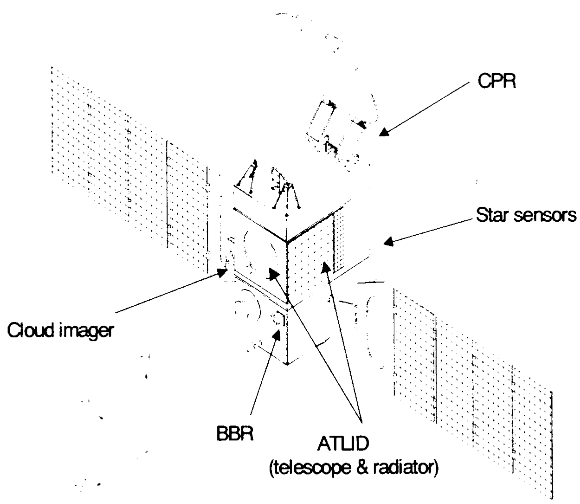

Figure 4: ERM In-orbit Configuration

In this so-called stacked configuration, the ATLID box structure provides the load paths between the platform and the CPR, minimising overall satellite mass and complexity. The passive instruments, although smaller in size and less demanding, have to meet viewing requirements for nadir looking and sun/space calibration. The BBR and CI are accommodated on the platform to simplify mechanical interfaces and to satisfy these viewing requirements.

The design of the platform, housing all the support functions, is derived from concepts well proven on other satellite projects. Existing designs and hardware will be reused to the maximum extent possible. The platform configuration has been optimised to serve as an interface to the launcher and to offer sufficient volume and area for subsystem accommodation.

The mechanical design of the uncanted solar array, is derived from Globalstar project. Its accommodation is determined by the need to minimise viewing obstructions of the ATLID radiators. Total panel area of the array is about 11.5 m^2.

SATELLITE ARCHITECTURE

The platform is based on the LEOSTAR platform design of MMS.

The attitude and orbit control system uses reaction wheels and magnetorquers for the generation of the required control torques with inputs from star sensors, sun sensors, gyros and magnetometers. A GPS receiver is used for navigation and the generation of precision timing signals. Orbit control is performed by a hydrazine propulsion system.

Data management is centralised in a single computer which performs all necessary instrument and platform processing functions. Low rate instrument data are acquired via a MIL 1553 bus from the CPR, CI and the BBR, while the high-speed data generated by ATLID is acquired via a dedicated serial interface. Command and control data are transmitted via the MIL 1553 bus as well.

All attitude and orbit control processing functions are resident in the central computer, the data being transmitted via a mixture of digital and analog lines.

All science and housekeeping data are stored in a solid-state mass memory housed in the same box as the computer and transmitted to ground via X-band. The design of the X-band transmitter is driven by the data rate of 20 Mbps which is necessary for the transmission of all data collected during one day. A solid state transmitter with an output power of 8 W is used with dedicated QPSK modulators. Data are Reed-Solomon (R-S) encoded in order to improve the link budget. The design of the shaped gain antenna will be adapted from ongoing projects.

Housekeeping data are down-linked separately via an S-band transponder which is used also for telecommanding. The S-band transponder is redundant for both the uplink and downlink chains, a 3dB hybrid providing the coupling to the two hemispherical antennas for omni-directional coverage.

The power system consists of a two-wing solar array, with a single 24 cell 50 Ah NiH_2 battery for the operational phase, completed with a $LiMnO_2$ primary battery for the launch phase. GaAs cells are selected, rather than Si as used on Globalstar, to minimise the array area and hence the drag effects.

GROUND SEGMENT

The ERM ground segment consists of three functional elements. The Command and Data Acquisition Element (CDAE), the Mission and Satellite Control Element (MSCE) and the Processing and Archiving Element (PAE). The ground segment architecture proposed for ERM reuses the Agency's existing infrastructure in Kiruna, ESOC and ESRIN to the maximum extent possible.

The following definitions apply for data processing :

- Level 0: Unprocessed data in chronological order at full space/time resolution with all supplementary information to be used in subsequent processing (e.g. orbit data, time, etc.) ;
- Level 1: Pre-processed geo-located payload data in chronological order at full/time resolution with all corrections (geometric, radiometric, etc.) appended ;
- Level 2: Fully processed geo-located geophysical products.

The data from the Earth Radiation Mission is to be used mainly in an off-line mode. This can be achieved with a single ground-station (e.g. Kiruna) with adequate archiving facilities. Due to their relative simplicity, some of the Level 1 products may even be generated in a completely automatic mode.

However, due to the interest in ERM data from operational weather forecast organisations, it is highly desirable to have a near-real-time (3 to 6 hours) delivery of the Level 0 products as well as Level 1 products that can be produced in a completely automatic basis. These data would not be provided in near real time for the whole globe due to the baseline of one ground station but the approximately one-third of the Earth covered in near real time would nevertheless be of high interest.

CONCLUSION

The Earth Radiation Mission was not selected in 1999 as one of the next Core Earth Explorers however a joint mission with Japan is being pursued. All the preparation work for this mission has lead to significant scientific development, especially in the retrieval techniques, that may be used in a future joint mission.

In the technology area. No design issues have been identified which would require development of new technologies or extensive development efforts. The instruments have a good heritage of technology studies and novel design concepts are mature as far as their design definition is concerned. Further detailed design and manufacturing do not pose risks beyond the level of normal engineering work.

The platform design concept is based on the re-use of existing principles and, where possible, existing hardware, minimising risk and cost. The successful drive for a small to medium-size system has allowed a launch vehicle to be selected at the lower end of the cost range. Rockot's heritage provides good prospects for successful operation and ERM spacecraft mass at launch (< 1000 kg) lies well within its capabilities providing a system mass margin of around 20%.