CPR DESIGN AND DEVELOPMENT STATUS FOR THE ESA EARTH RADIATION EXPLORER MISSION

C.C. Lin[1], W. Leibrandt[1], U Mallow[2], and R. Bordi[3]

1) ESTEC, PO Box 299, 2200 AG Noordwijk, The Netherlands
Tel.: +31-71-5655813, Fax.: +31-71-5654696, E-mail: clin@estec.esa.nl
2) Dornier Satellitensysteme, 88039 Friedrichshafen, Germany
3) Alenia Aerospazio, Via Saccomuro 24, 00131 Rome, Italy

1. INTRODUCTION

The Cloud Profiling Radar (CPR) is one of the payload instruments on board the Earth Radiation Explorer Mission (ERM) spacecraft [1]. The primary goal of the CPR is to determine the altitude of cloud boundaries and to provide vertical profiles of cloud structure along the satellite s flight track. The radar beam is co-aligned with that of the backscatter lidar, the second active payload instrument, in order to permit quantitative (synergical) retrieval of cloud microphysical properties.

The CPR is a nadir pointing, pulsed radar operating at a frequency of 94.05 GHz which would permit measurements though cloud layers almost down to the Earth surface level, making it an indispensible sensor for this mission. Due to the generally low reflectivity of clouds, the major challenge for designing the radar is to maximise its sensitivity and at the same time maintaining an acceptable vertical resolution.

This paper gives a summary description of the instrument design at the end of an industrial phase A study [2], its innovative features and technology status of a number of critical items.

2. INSTRUMENT REQUIREMENTS

The instrument requirements summarised in Table 1 have been derived from the measurement requirements of the corresponding mission geophysical products [1].

The 94.05 GHz radar frequency has been identified as a best choice in terms of sensor sensitivity and has specifically been allocated for cloud profiling radar applications. The sensing altitude range extends from 0 to 20 km measured from a reference geoid. Two different vertical resolutions are required: 500 m in nominal mode and 350 m in secondary mode. This would allow a higher flexibility in utilisation of the radar according to the statistics of the globally observed cloud reflectivity and layer thickness. Correspondingly, two different sensitivity figures have been put for the nominal and secondary modes, respectively. This sensitivity requirement is applicable for a target cloud layer centred at 1 km altitude, of 500 m and 350 m thickness for the two respective modes, respectively, under two thin cloud layers (Cirrus and Alto-Stratus clouds) assuming a mean annual tropical atmosphere (see Table 2). Such a scenario assumption represents a rather severe attenuating condition for the radar signal and ensures a sufficient sensitivity for most climatic conditions.

The total radiometric accuracy of 1.7 dB is for an assumed along-track integration distance of 10 km and it shall include all error sources such as radiometric resolution, stability, other random errors and residual calibration errors.

Table 1: CPR instrument requirements

Parameter	Value
Transmit frequency	94.05 GHz
Polarisation	Linear
Radar beam pointing	Nadir (ATLID co-aligned)
Sens. altitude range	0 20 km
Vertical resolution	≤ 500 m (nominal mode) ≤ 350 m (secondary mode)
Vertical sampling	100 m
Horizontal sampling	1 km
Instantaneous footprint	≤ 1000 m
Minimum Z (at 1km altitude)*	≤ -33 dBz (nominal) ≤ -30 dBz (secondary)
Maximum Z	≥ +20 dBz
Radiometric stability	≤ 0.3 dB over orbit ≤ 0.5 dB over mission
Total radiometric accuracy	≤ 1.7 dB (for 10 km integration)
Mission duration	≥ 2 years

*) - Atmospheric model = annual mean tropical with 1.21 dB total zenith attenuation (one-way) at 1 km altitude
- Cloud model = 3 layers with:
(1) 0.75 km ≤ target cloud ≤ 1.25 km
$|K|^2 = 0.6856$, Im(-K) = 0.1876
(2) 4 km ≤ Alto-Stratus ≤ 4.5 km
$|K|^2 = 0.5971$, Im(-K) = 0.2006
(3) 8.5 km ≤ Cirrus ≤ 9 km
$|K|^2 = 0.1760$, Im(-K) = 1.46×10^{-6}

3. DESIGN APPROACH

The instrument design has been driven by the goal to achieve a highest sensitivity within the whole sensing altitude range. This can usually be achieved using pule compression technique in order to increase the electromagnetic energy within each transmitted pulse. Unfortunately, the reflectivity of the Earth surface could be higher than that of the target cloud by more than 75 dB (e.g. for calm ocean). Consequently, this imposed an extremely tight range-sidelobe requirement of better than 75 dB to be achieved by the compressed pulse which was technically unfeasible. For this reason, a short, unmodulated pulse scheme with a high peak transmitter power was selected.

The high sensitivity requirement led to the use of quasi-optical radar frontend concept for minimising losses within the radar chain and an InP-based LNA technology which offers very low noise figure. A maximum antenna size still compatible with the candidate launcher was selected and a lowest possible orbit altitude of 380 km has been baselined for achieving a best radar link-budget. The resulting single-pulse SNR is still around 15 dB for the worst case target cloud, implying a necessity to average a large number of pulses for achieving the required radiometric accuracy.

The generally low signal level of the cloud returns with respect to that of the receiver noise implies that a very accurate estimate of the noise level is required for an unbiased measure of the radar echo. Indeed, a noise level estimation error of 0.1 dB could result in a cloud reflectivity bias error of approximately 2.4 dB for a 33 dBz cloud. Hence, a very accurate and continuous measurement of the receiver noise, which also varies according to the Earth blackbody radiation (antenna temperature) over various surfaces, must be a part of the receiver functions.

4. BASELINE DESIGN

The overall instrument architecture is shown in Fig. 1 with the current baseline using the quasi-optical design for the radar frontend. The CPR mechanical configuration is shown in Fig. 2 together with the details of the quasi-optical frontend (right). The CPR configuration is dominated by the large reflector, which together with the smaller sub-reflector forms a Cassegrain (dual-offset) type reflector system. The aperture dimension of 1900 mm × 2150 mm has been optimised to fit into the fairing of the reference launch vehicle. The dish is made of a CFRP/Al sandwich with longitudinal and lateral stiffening ribs. It will be folded against the upper panel of the frontend assembly box for launch.

A schematic layout of the quasi-optical frontend and antenna is depicted in Fig. 3. A quasi-optical diplexer (Faraday rotator) is used to separate the transmit and receive paths. As a backup solution, a waveguide-based design has also been investigated (see Fig. 4), which would exhibit a slightly degraded instrument sensitivity (approx. 1 dB). Although this concept is considered more mature than the baseline, its performance critically depends on the waveguide circulator, which is currently not available in a space qualified version.

The transmit channel uses an Extended Interaction Klystron (EIK) amplifier. The high power amplifier, together with its Electronic Power Conditioner (EPC) will be redundant, not only because of mission life, but also because of potential failure considerations.

The receiver channel consists of a redundant set of passively cooled low noise amplifiers (LNA). The LNA includes the mixer for down-conversion to the first intermediate frequency at 11.5 GHz.

The radar back-end consists of the Millimetre-wave Frequency Generator (MMFG), shared by the transmit and receive channels and the Radio Frequency and Processing Unit (RFPU). The MMFG consists of an Ultra-Stable master Oscillator (USO) operating at 100 MHz and the multiplier circuits for generating the local oscillator signals for the receiver and the input signal for the transmitter. The RFPU contains the up- and the down-conversion chains as well as the mode control and data handling units. The final signal detection is performed by digital convolution. The Pulse Repetition Frequency (PRF) has to be adapted to the range between the satellite and the mean geoid, which is not constant for the chosen orbit configuration. It will be controlled by a look-up table residing in the CPR back-end.

Table 2 below summarises the instrument design parameters.

Table 2:CPR instrument design parameters

Inst. parameter	Value
Antenna aperture Effective area	1900 mm × 2150 mm 2.1 m^2
Pulse length	3.33 μs (nominal mode) 2.33 μs (secondary mode)
PRF	5310 5696 Hz
Echo vs. noise meas. sequence	6 echos/noise (nominal) 7 echos/noise (secondary)
Peak RF power	≥ 1.5 kW (EIK amplifier)
Tx/Rx losses	1.13/2.63 dB (1.8/3.0 dB for waveguide option)
LNA physical temp. Noise figure (NF)	≤ 240° K ≤ 3.5 dB
Processing loss	≤ 0.4 dB

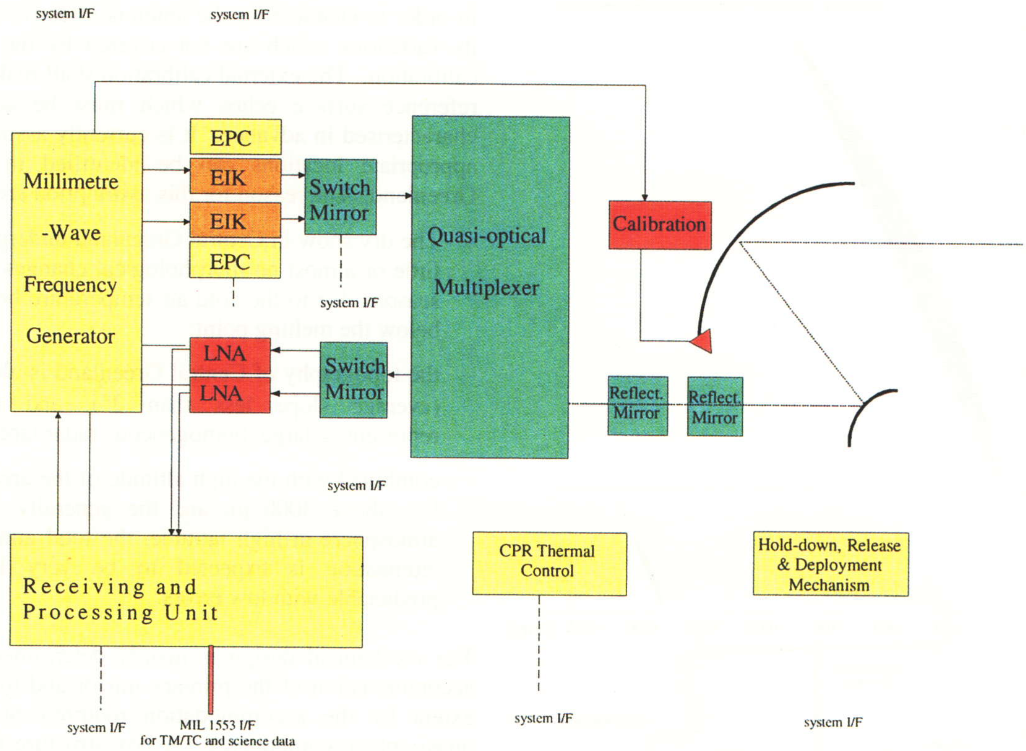

Fig. 1: CPR functional block diagram

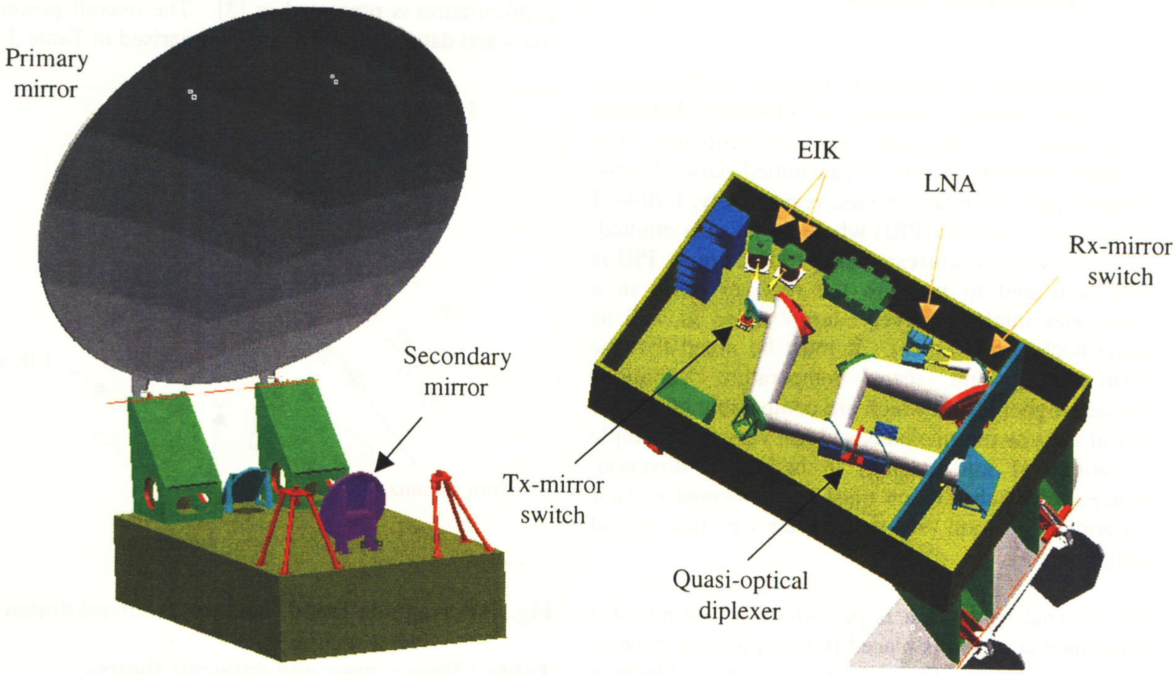

Fig. 2: CPR instrument configuration (left) and inside view (right) with quasi-optical beam path (-40 dB contour in white)

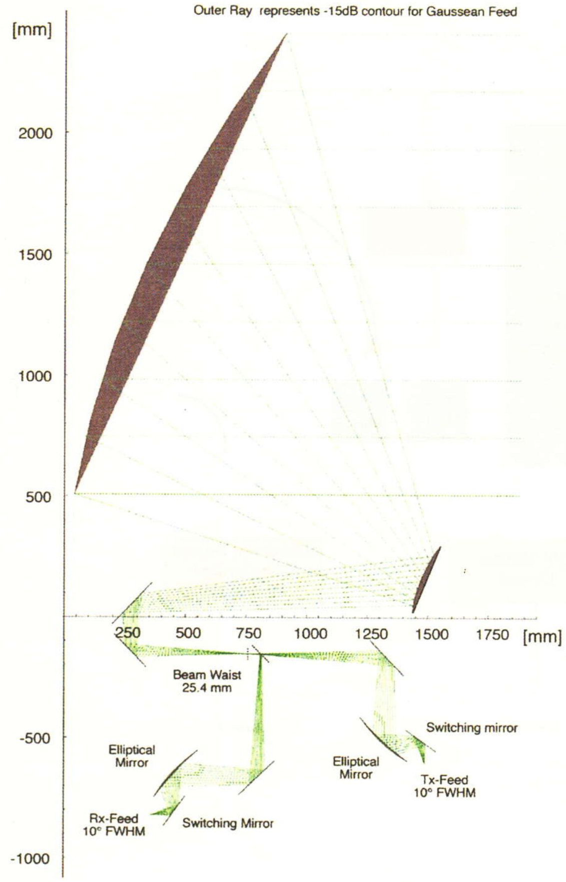

Fig. 3: Schematic layout of the quasi-optical frontend and antenna

The requirement to accurately measure receiver noise led to the solution consisting of allocating dedicated noise windows in the pulse repetition sequence. The sequence consists of 6 or 7 transmitted pulses for the nominal and secondary modes, respectively, followed by an empty interval (PRI) where no pulse is emitted. The echo-window corresponding to this empty PRI is then dedicated to measure the receiver noise in a radiometer mode (receiver internal noise as well as scene background noise). It must be noted that the Earth background scene temperature variations produce signal levels which are comparable or exceed that of the low return clouds and can vary from sample to sample (1 km spacing) in horizontal direction. Hence, noise substraction must be performed at each horizontal position so as to remove this signal component.

The internal calibration is performed by means of a horn antenna which is placed in the spill-over zone of the main reflector. Through this horn, the calibration subsystem samples the transmit pulses and also injects calibration signal so as to completely characterise the gain of the internal radar chain within each PRI. Regular in-orbit external calibrations are also required in order to characterise the antenna effective area and its variations which are not covered by the internal calibration. The external calibration shall make use of reference surface echos which must be accurately characterised in advance. It is currently assumed that appropriate locations can be identified in Central Greenland. The reason for this assumption are:

- The dry snow in Central Greenland undergoes very little or almost no morphological changes over the seasons due to the cold air temperature being well below the melting point:
- the topography of Central Greenland is almost flat (average slope less than 2°), and therefore represents a large, homogeneous radar target:
- combined with the high altitude of the area, which lies above 3000 m, and the generally very dry atmosphere at high latitude, the total atmospheric attenuation is expected to be very low and predictable with low errors.

The mechanical design is mainly determined by the accommodation of the primary mirror and to a lesser extent by the accommodation requirement for the quasi-optical components. A box structure has been selected, which also houses the electronics boxes and interfaces with the ATLID support structure. The thermal dissipation of the EIK amplifier and the EPCs is the dominating driver for the thermal design. These units have therefore been accommodated on the anti-sun and zenith faces of the CPR structure in order to maximise the heat radiation. The overall satellite configuration is presented in [3]. The overall power, mass and data-rate figures are summarised in Table 3.

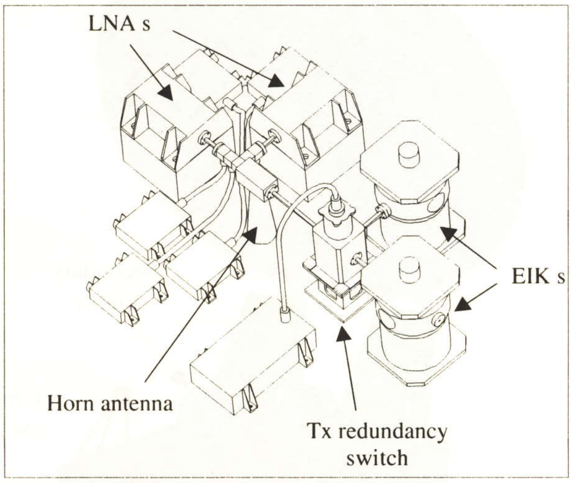

Fig. 4: Waveguide-based (backup) frontend design

Table 3: Power, mass and data-rate figures

Power	272 W (15 % margin included)
Mass	136 kg (20 % margin included)
Data-rate	30 kbits/s (1 km on-board averaging)

5. PERFORMANCE

Table 4 summarises the CPR s performance, as predicted at the end of Phase A, measured under a cloud and atmospheric model scenario as indicated under Table 1 and for a signal integration distance of 10 km.

The accuracy with which the altitude of cloud boundaries can be determined depends on three factors: the vertical resolution, the probability of detection for thin clouds and the altitude knowledge with which the signal samples can be positioned. In particular, the probability of detection is determined by the instrument s radiometric resolution and is worst at the bottom of the atmosphere (e.g. at 1 km). The positioning knowledge of the samples is a function of the satellite pointing and attitude determination accuracy as well as the instrument timing accuracy. Cloud boundaries can be estimated with an accuracy of better than 197 m in the nominal and 138 m in the secondary mode.

Note that the $|K|^2$ value of 0.6856 which was used for the performance estimation corresponds to the dielectric constant of water at a temperature of 0° C (the worst case for non super-cooled water) measured at 94 GHz. Often, a different normalisation value of 0.93 is used by radar meteorologists for other reasons which would increase the radar reflectivity of cloud particles by approximately 1.3 dB. Hence, the estimated CPR sensitivity would improve by 1.3 dB if the latter value was used.

For illustration, instrument sensitivity is listed in Table 5 for a single water-cloud layer at various altitudes: layer thickness is 500 m for the nominal and 350 m for the secondary mode. Only a clear atmosphere attenuation is taken into account for this calculation. The corresponding data for mid-latitude summer atmospheric conditions are also shown. Those performance figures meet the CPR requirements laid down in [1].

Table 4: CPR performance data

Performance param.	Value
Instantaneous footprint	706 m diameter (-3 dB one-way)
Receiver noise temp.	865° K
Vertical resolution	500 m (nominal) 350 m (secondary)
Vertical positioning knowledge of samples	≤ 50 m
Noise equivalent Z	≤ -17.6 dBz (nominal) ≤ -14.5 dBz (secondary)
Minimum Z (for 10 km integration)	≤ -32.3 dBz (nominal) ≤ -29.4 dBz (secondary)
Upper dynamic range	+27 dBz (nominal) +30 dBz (secondary)
Radiometric resolution	≤ 1.44 dB
Radiometric stability	≤ 0.3 dB over orbit ≤ 0.5 dB over mission
Total radiometric accuracy	≤ 1.7 dB
Cloud-base localisation	≤ 197 m (nominal) ≤ 138 m (secondary)

Table 5: Sensitivity for a single cloud layer of 500 m thickness (nominal mode) and 350 m thickness (secondary mode) after 10 km integration ($|K|^2 = 0.6856$)

Altitude [km]	Mean Annual Tropic (req.)	Summer Mid-Latitude
	Nominal /Secondary [dBz]	Nominal /Secondary [dBz]
0.5	-32.3 /-29.5	-33.4 /-30.6
1.0	-33.1 /-30.3	-33.9 /-31.1
2.0	-34.2 /-31.4	-34.5 /-31.7
4.0	-35.1 /-32.3	-35.2 /-32.4
6.0	-35.4 /-32.6	-35.4 /-32.6
8.0	-35.5 /-32.7	-35.5 /-32.7
12.0	-35.5 /-32.7	-35.5 /-32.7

6. DEVELOPMENT STATUS

As far as technological or development issues are concerned, a number of areas have been identified requiring dedicated efforts. These are the adaptation of the EIK to space-flight standards, detail design of the Faraday rotator for the quasi-optical diplexer, or the circulator for the waveguide option (backup solution). The EIK related activities have been started sufficiently early within ESA in order to overcome the generally long lead-time necessary for such a development. A first test EIK has been built using a Triple-Alloy (TA) cathode and the cathode life-test programme has been started (on-going fabrication of test diodes and automated test power supply). Regarding the quasi-optical diplexer and circulator, a first breadboard activity has just been initiated for assessing their power handling capability in space environment and expected losses. Whilst these issues are to be considered technically challenging, their criticality is well within the limits of normal instrument development.

In other areas, technological advancements are desirable in order to increase the design margins or to improve reliability. Notable examples are the LNA based on InP MMIC technology for achieving very low noise performance, the W-band GaAs MMIC driver amplifier with sufficient output power for driving the EIK and the high efficiency/low mass EPC for the EIK. A summary of the critical areas and on-going development activities is given in Table 6.

Table 6: Critical items/areas and on-going development activities

Subsystem/equipment	Critical item - Area	On-going developments
High power amplifier	Extended Interaction Klystron - Performance, life-time and space qualification	• EIK tube with new TA cathode built and tested (test vehicle) • Cathode life-test programme initiated with batch of diodes
	Electronic Power Conditioner (high voltage power supply) - Reliability of Wehnelt modulator with its high voltage swing	Functional breadboard in development
Antenna/quasi-optics	Quasi-optical diplexer and waveguide circulator (backup) - Power handling capability and losses	Breadboarding initiated
Receiver	Low noise amplifier - Very low noise performance	InP-based MMIC prototype in development
	1st down-converter - Image rejection requirement and low conversion loss	InP-based MMIC prototype in development
Radar back-end	Up-conversion/driver amplifier - Sufficient driving power	GaAs MMIC prototype in development
	Up/down-conversion chain - Very low range-sidelobe requirement	Functional breadboard completed and ≥ 80 dB range-sidelobe attenuation demonstrated

7. REFERENCES

[1] Earth Radiation Mission, Reports for Mission Selection The Four Candidate Earth Explorer Core Missions, ESA Publication SP-1233 (3), July 1999.

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[3] J.P.V. Baptista, A. Culoma, P. Ingmann, W. Leibrandt, C.C. Lin and R. Meynart, The Earth Radiation Mission: The Role of Clouds and Aerosols, Proc. of the 1st Int l Workshop on Spaceborne Cloud Profiling Radar, 24-26 Jan. 2000, Tsukuba, Japan.