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OPERA A SMALL-SIZE CONCEPT FOR EARTH RADIATION BUDGET SCANNING RADIOMETERS

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ABSTRACT *- SFIM Industries has designed a new radiometer for satellite observation of the earth radiation budget at the top of the atmosphere. Compared to previous instruments, this new radiometer halfs costs, mass and probability of failure, while it improves radiometric performance significantly. The key idea to achieve these goals is to multiplex the various spectral channels of the instrument. This paper describes this new small size instrument and focuses on its advantages and shortcomings.*

1. INTRODUCTION

OPERA (Observation Program for Earth Radiation Assessment) is a spaceborne cross-track scanning radiometer aimed at measuring the earth radiation budget (ERB) at the top of the atmosphere. The ERB is a key element in understanding the variability and evolution of the earth's climate. OPERA will for instance provide data needed to study the influence of clouds on radiative exchanges, explain climate variability and anomalies (e.g. El Nino Southern Oscillation). It will also help understand energy transfer between regions on earth, as well as long term global climatic changes.

OPERA builds on the experience of the ScaRaB instrument, a cross-track scanning radiometer developed for CNES by the Laboratory of Dynamical Meteorology of CNRS with SFIM Industries, and launched in January 1994 on a METEOR-3 Russian satellite. A second ScaRaB radiometer is scheduled for launch on a RESURS satellite in 1998.

OPERA has been especially designed in view of missions on-board small satellites. To give this new generation of instruments a chance to materialise, very challenging objectives were defined, viz. half costs, mass and probability of failure, while improving radiometric performances. Furthermore, the proposed design will have to demonstrate state-of-the-art performance in a decade. An adaptation of OPERA to CNES TROPIQUES mission is currently being studied.

The key design change to achieve the demanding goals set for the study was to reduce the number of detectors from four on ScaRaB to one and hence to multiplex spectral channels. Mechanisms, electronics and calibration sources can then be descoped, while intercalibration between channels and co-registration of the various spectral channels are greatly eased. Finally, integration and test activities are shortened and reliability is dramatically improved. This paper focuses on space segment design.

2. INSTRUMENT PRINCIPLE

The ERB stakes as well as the fundamental principles of its measurement have been reviewed by Kandel [Kand 90]. ERB observation consists in mapping sources and sinks of energy at the top of the atmosphere. The incoming solar radiation being obtained from measurements made by other experiments, the ERB components are the reflected solar exitance and the outgoing long-wave exitance (in W m^{-2}).

A radiometer for ERB observation gives outputs which are proportional to *filtered radiances* (in W m^{-2} sr^{-1}) in two broadband channels. Filtered radiances are integrated spectral radiances weighed by the instrument spectral response. A solar channel (0.2 μm to 4 μm) is used to determine the reflected solar filtered radiance, while the outgoing long-wave filtered radiance is derived from the difference between a total channel (0.2 μm to 200 μm) and the solar channel. Spectral correction factors which account for the fact that the instrument spectral response is not perfectly flat are computed and applied to solar and total filtered radiances to obtain *solar and total integrated radiances*. As these spectral correction factors depend on the observed scene spectrum, proper scene identification is required. This identification is performed with the help of two additional channels with narrower bands in the near infrared and thermal infrared (see Fig. 1).

Taking into account radiance anisotropies, the scene radiance is then integrated over the hemisphere to obtain the scene exitance, which is the quantity needed by scientists. In most cases, this exitance varies throughout the day and an additional correction is applied to account for these variations.

Instrument biases are measured by sighting cold space (zero radiance). The detection chain gain used to translate numerical counts into solar and total filtered radiances is monitored by viewing a highly stable calibrated hot scene (on-board blackbody simulator). On-ground absolute calibration of the on-board blackbody simulator allows us to relate its radiance to a primary standard, and hence to compute the instrument gain.

To monitor the variations of shortwave spectral response, an in-flight solar calibration device is used. As a matter of fact, in-flight spectral response changes are negligible in the infrared and need only be monitored in the shortwave domain.

To accurately subtract the solar filtered radiance from the total filtered radiance, one needs to take into account the difference between the responses of the solar and total channels in the shortwave domain. This difference is characterised for each type of scene by a cross-calibration factor which can be determined on-ground for a large set of scene spectra. The in-flight variations of cross-calibration factors are monitored thanks to the solar calibration devices.

3. INSTRUMENT DESCRIPTION

3.1. Instrument overview

OPERA is a cross-track scanner comprised of a scanning head and an electronics box. The scanning head accommodates the rotor, the scanning mechanism and the on-board calibration sources. These various subsystems are briefly described below for an instrument designed for a mission from an 800 km heliosynchronous orbit with 10 h equator crossing time. OPERA's four spectral bands are

Solar	0.2 μm to 4 μm
Total	0.2 μm to 200 μm
Near Infrared (NIR)	0.6 μm to 2.75 μm
Thermal Infrared	10.5 μm to 12.5 μm

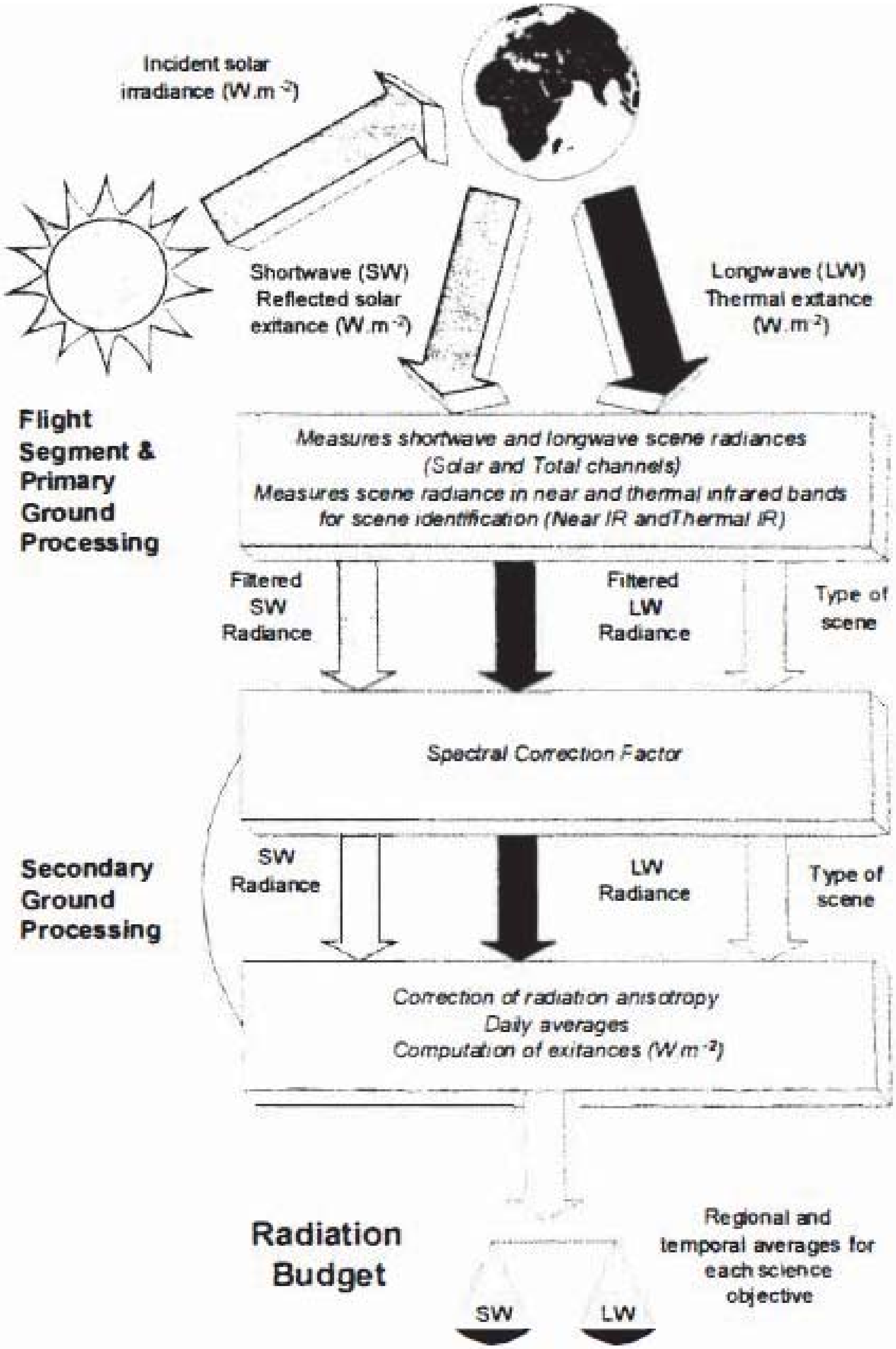

Fig. 1 : Earth radiation budget measurement principle

OPERA represents a major breakthrough with respect to previous instrument like ScaRaB [Mong 91] in that it can measure spectral bands *sequentially* a single detector is used, avoiding the need for several mechanisms and electronic boards

3.2. Rotor design

Each spectral band is defined by a filter, except the total band which does not require any. For in-flight calibration purposes there are two material channels in the total band (see Fig. 2). These five apertures are placed on a fixed filter-holder in front of which a clear aperture revolves at a constant speed of 25 revolutions per seconds. This mechanism, called a channel selector (see Fig. 3), allows radiation coming from the earth to go through one aperture at a time. Radiation then strikes an aspheric aluminium mirror and is focused onto the detector. The mirror has a 62.5 mm focal length and an f-number of 1.

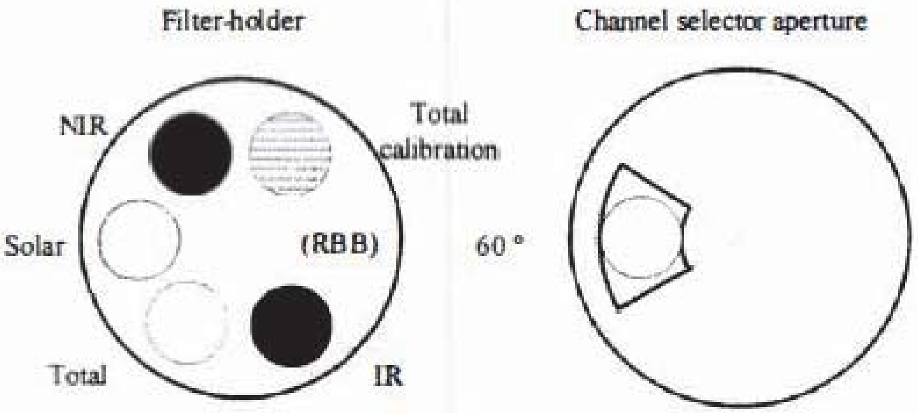

Fig. 2 : Filter-holder and channel selector aperture

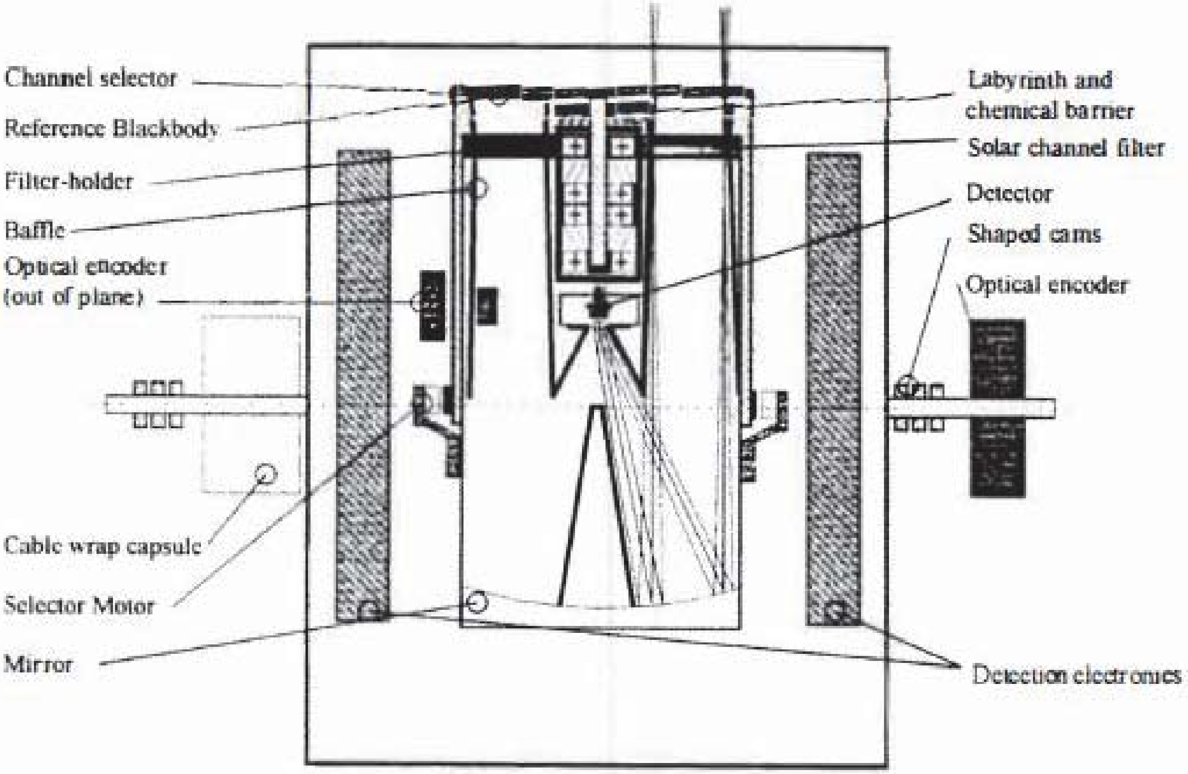

Fig. 3 . Sketch of Rotor

OPERA's detector is a 3 by 3 mm windowless $LiTaO_3$ pyroelectric detector coated with a thin black absorbing layer. Pyroelectric detectors do not respond to DC input and chopping is therefore required. The channel selector fulfils this chopping function with no additional mechanism. A reference level is given by a reference blackbody (RBB) which remains thermally stable during a complete scan cycle and whose radiance therefore does not vary by any significant amount.

Channel selector lifetime is a critical issue as a four year mission requires over 3 billion revolutions. Redundant ball bearings with fluid lubrication provide a reliable low cost solution. A brushless synchronous motor with magnets on the rotor and an optical encoder are used to drive the channel selector disc.

Filter in-flight stability is a driving parameter for overall performance, primarily on the solar channel. The filter placed on this channel is made of bulk suprasil silica whose insensitivity to space radiation has been proven [Kemp 93]. The NIR channel band is made of a coloured glass window shielded against radiation by a suprasil silica window. The thermal infrared channel uses an interferential filter identical to Meteosat's.

Filters are made slightly prismatic (up to about 2° on the NIR channel) to compensate for the instrument line of sight rotation between acquisitions on the total channel and on a channel equipped with a filter. The instantaneous fields of view (IFOV) of two different spectral channels are thus made to coincide spatially (channel registration) despite continuous scanning of the rotor. The multiplexed configuration eliminates stringent alignment requirements and significantly improves channel registration.

Detector output is filtered and amplified by the detection electronics. This signal is then sampled when the channel aperture is totally unobstructed by the channel selector disc, and digitised as 14 bit words. This yields a dynamic range larger than 600 $W\,m^{-2}\,sr^{-1}$ on any channel.

3.3. Earth sampling and scan cycle description

OPERA is equipped with a pendulum scanning mechanism which is used for across-track earth sampling. Along-track scanning is provided by the spacecraft as it orbits the earth. The scanning mechanism is also used to let the rotor view cold space or calibration sources located at the end of the scan line.

The IFOV of the instrument is a 2.75 ° square which yields a resolution better than the required 40 km at nadir. The instrument earth scan speed is adjusted so that pixels along the scan line are contiguous (see Fig. 4.). Similarly, the scan period is chosen so that two consecutive lines are also contiguous. Finally, as it is important to measure daily the global distribution of shortwave radiance, two earth scan swaths in a row are set edge to edge. This requires the earth swath to be about 2870 km or +/- 55°. There are therefore 40 pixels in each scan line and the complete scan cycle lasts 5.8 s

In order to save power, the rotor is designed to behave as much as possible like a harmonic oscillator (see Fig. 6.). This scanning philosophy also minimises rotor accelerations which disturb spacecraft stabilisation. The earth is scanned twice per scan cycle, but the various spectral channel are correctly registered (see § 3.2) during one of the two scans only.

A blackbody simulator (BBS) is viewed at every scan cycle by the total channel at one end of the scan line, while the solar and total-calibration channels view the in-flight solar calibration device (Solarcal) at the other end, even when the sun is not seen through it. This straightforward operating principle avoids the need for calibration modes and simplifies software and testing. All five channels view a zero reference radiance during two short periods as the rotor scans deep space, away from the earth's limb.

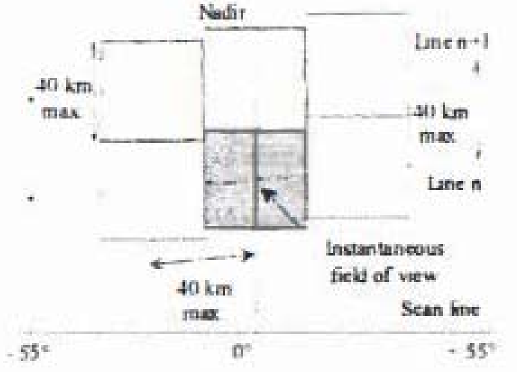

Fig. 4 : Sampling pattern

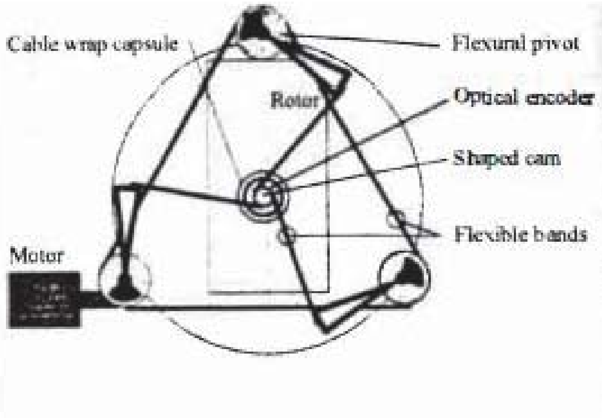

Fig. 5 : Sketch of scanning mechanism

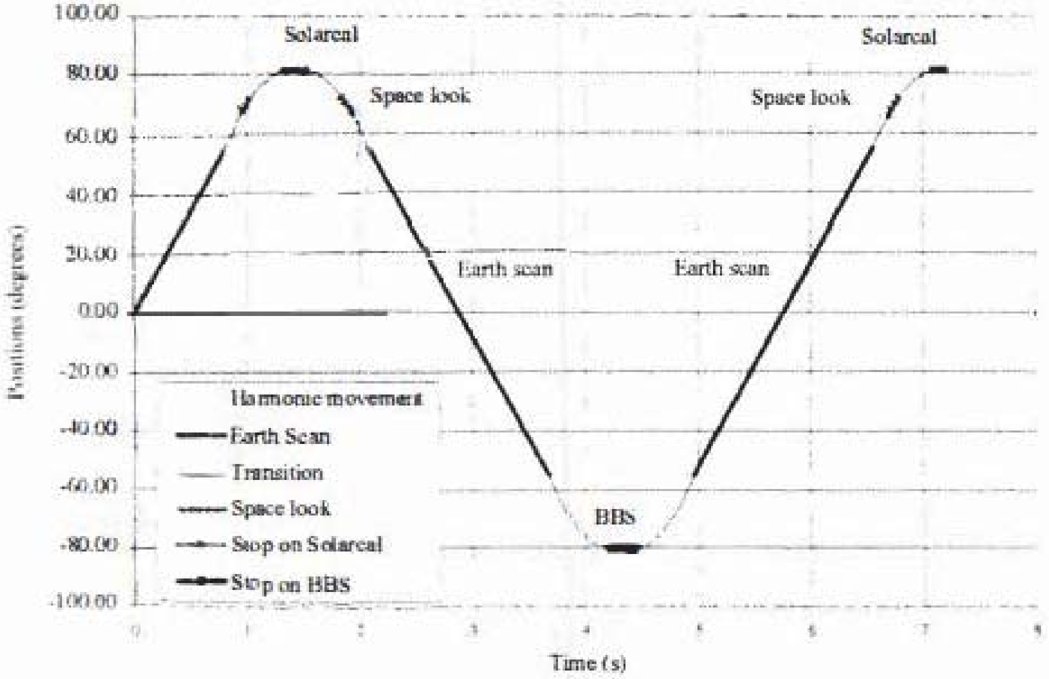

Fig. 6 : Scan cycle

3.4. Scanning mechanism

To avoid lubrication problems on ball bearings loaded with a non-negligible rotor mass, a scanning mechanism which relies only on flexible parts has been proposed. The scan axis is mechanically defined by six flexural pivots, three at each end of the rotor (see Fig. 5). A phinox band is attached to each flexural pivot, with the other end of the band being fixed on a cam mounted on the rotor shaft. As the rotor scans, these bands wind and unwind on the shaft and the pivots. To ensure that all bands remain tight throughout the scan cycle, the pivots are preloaded. While three bands at one end of the rotor wind on the cams - and unwind from the pivots -, the other three bands at the other end of the rotor unwind from the cams. As the scan angle increases, so does the return torque produced by the three pivots from which the bands are unwound, while the torque produced by the three other pivots goes down, and this causes the rotor to oscillate.The diameter of the shaft is chosen to be one tenth of the diameter of the pivot, so that the angular travel of the pivots is ± 8.1°, i.e. well within the infinite life range.

Translating of the scan axis in a plane perpendicular to the scan axis would result in one pivot, out of the three at each end of the rotor, unwinding when the other two pivots would wind. Such translations are prevented thanks to an additional band bonded to all three pivots like a belt, which forces all of them to rotate in the same direction.

The function of the motor is to slightly alter the scanning behaviour of the oscillator to suit the desired scanning law (see Fig. 6) and to compensate for residual friction. Thanks to the limited travel of the pivots, a coil moving between the jaws of a permanent magnet makes a suitable, cheap and reliable linear motor. An optical encoder provides the scan angle information needed to drive the motor. Finally, a cable wrap capsule is used to route electrical wires to and from the rotor.

3.5. In-flight calibration

The in-flight calibration strategy already outlined (see § 2 & 3.3) is summarised in Fig. 7.

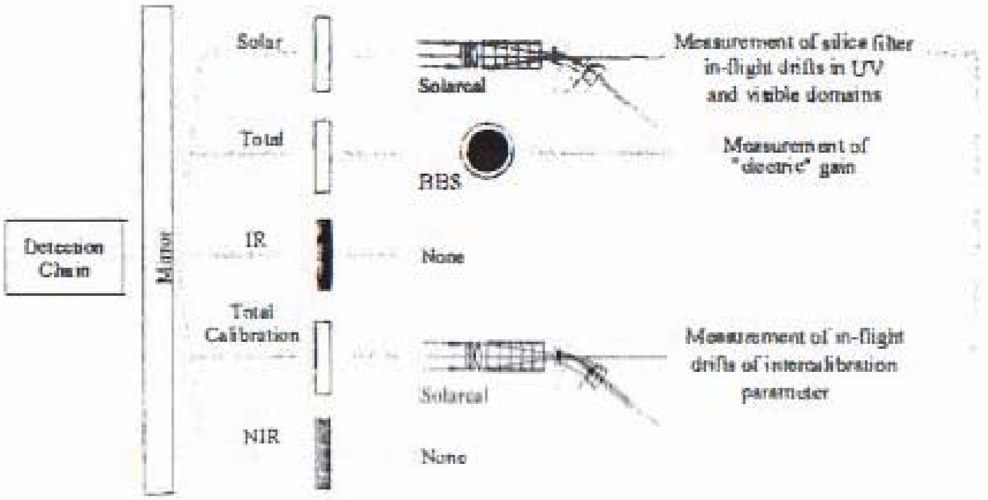

Fig. 7 : Principle of in-flight calibration

The blackbody simulator (BBS), which is made of concentric metal lighttraps, is used to determine the absolute gain of the instrument in the infrared where its spectral response is flat. The solar calibration device (Solarcal [Care 95]) on the contrary measures ageing of the spectral response in the shortwave domain. Obviously, the key performance of Solarcal is the stability of its spectral transmission. The diffusing element - a very cheap transmission diffuser - is made of suprasil silica (see § 3.2) like any other optical part used in Solarcal, and is well protected from contaminants. Fig. 8 shows the accommodation of calibration sources on a mock-up of the instrument.

3.6. Spectral response

As was mentioned earlier, an ERB radiometer should have a perfectly flat spectral response over the whole range of observed wavelength. However, neither mirror coating nor detector absorbing layer nor filter transmission are flat from 0.2 to 200 µm. Furthermore, a non-flat response over this whole range might be preferred to a flatter response in a more limited range. OPERA's spectral response is measured on-ground by comparison to that of a wedge of pyroelectric detectors which acts as a light trap (hence with flat spectral response) and which is sensitive across the spectral range of OPERA. Fig. 9 gives the typical shape of the relative spectral response of the solar channel.

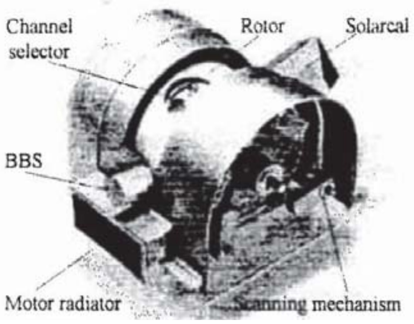

Fig. 8 . Accommodation of scanning head subsystems

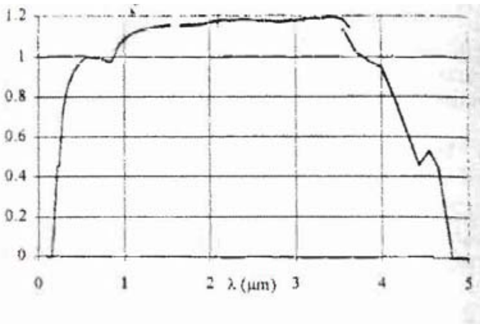

Fig. 9 Typical relative spectral response of solar channel

3.7. Thermal design

The major constraints on thermal design are related to the stability of the temperature of the surrounding of the detector - as the detector response varies with temperature - and to the stability of the reference blackbody temperature during the scan cycle. In order to reduce detector noise, its temperature shall be as low as possible.

Beside the usual requirements on temperature ranges set by electronic parts or bearings, the BB has special requirements. In order to control its temperature stability and uniformity, it must be kept at a slightly higher temperature than its environment. This temperature difference shall be as small as practical, not only to reduce power demand, but also to minimise the effect of reflection of background radiation by the radiant area.

3.8. Electronics design

The electronics box, which includes five boards, uses a single computer to command and control the scanning head as well as interface with the spacecraft. All control loops (scanning mechanism, channel selector mechanism and BBS temperature stabilisation) are digitised. Considering the limited amount of data produced by OPERA (about 5 kbits/s), no data processing is performed on-board.

4. RADIOMETRIC PERFORMANCE

The uncertainty on the determination of the shortwave and longwave radiances δL_{SW} and δL_{LW} can be written as:

$$\delta L^2_{SW} = \delta^2_{GSW} \cdot L^2_{SW} + \delta^2_{TSW} \qquad \text{and} \qquad \delta L^2_{LW} = \delta^2_{GLW} \cdot L^2_{LW} + \delta^2_{TLW}$$

δ_G terms are called *gain* uncertainties and δ_T terms *threshold* uncertainties, L_{SW} and L_{LW} are the integrated shortwave and longwave radiances respectively. δ_T terms represent the instrument output when it points at a zero radiance scene and account for instance for the detection chain random noise. δG yields uncertainties proportional to the measured radiance and are to a large extent caused by calibration uncertainties.

Table 1 summarises budgeted performances on δ_G and δ_T given as 1 σ uncertainties for 95% of a large set of typical scenes, corresponding to various geophysical characteristics of the scene, cloud cover or viewing directions The scenes are assumed to be permanent, uniform and infinite.

On night-time scenes, the total channel yields directly the longwave radiance, whereas on day-time scenes, the shortwave radiance has to be removed from the total radiance. As this subtraction adds significant uncertainties when most of the radiance lies in the shortwave spectrum (e.g. high cold tropical clouds), uncertainties on the longwave radiance are assessed separately for day-time and night-time scenes.

	Shortwave Radiance L_{SW}	**Longwave Radiance L_{LW} night-time**	**Longwave Radiance L_{LW} day-time**
Gain (%)	$\delta_{GSW} = \pm 0.55$	$\delta_{GLW} = \pm 0.2$	$\delta_{GLW} = \pm 0.2$
Threshold ($W.m^{-2}.sr^{-1}$)	$\delta_{TSW} = \pm 0.15$	$\delta_{TLW} = \pm 0.2$	$\delta_{TLW} = \pm 0.5$

Table 2 : Uncertainty of radiance measurement (main channels)

To avoid crosstalk between spectral channels, detector signal amplification has to span a large bandwidth so that transient signals generated when acquiring data on a spectral channel can tail off before the start of the measurement on the next channel. The larger the bandwidth, the smaller the crosstalk, but the larger the detection chain random noise. The design of the amplifier therefore requires careful optimisation.

5. IMPROVEMENTS MADE TO OPERA WITH RESPECT TO SCARAB

5.1. Radiometric performances

The reduced cost of OPERA has not been at the expense of degraded performances. On the contrary, on top of the fact that OPERA reuses types of detectors and longwave calibration sources whose outstanding performances and stability have been demonstrated in orbit, shortwave calibration and scene identification have been very significantly improved.

Unlike ScaRaB, which used tungsten lamps for shortwave in-flight calibration, OPERA will be equipped with solar calibration devices on its two main channels (see § 3.5) to provide better monitoring of the instrument spectral response in the UV / visible domains. On-ground characterisation of the spectral response will also be improved.

Shortwave spectral correction factors and intercalibration parameter show even stronger correlation with the output of the NIR channel than with ScaRaB's visible channel. This allows more accurate science data correction on-ground and reduces particularly shortwave gain uncertainties as well as longwave threshold uncertainties on day-time scenes.

As each individual channel embodies an off-axis mirror, one could expect the output of the channel to depend on the state of light polarisation of the measured scene. This sensitivity was however modelled to be negligible with respect to radiometric gain uncertainties.

5.2. Accommodation on spacecraft

The complete instrument is budgeted to weigh about 17 kg, slightly less than half ScaRaB's mass. The scanning head fits in a 36 x 20 x 26 cm^3 volume, and the volume of the electronics box is about 7 litres. The instrument averaged power demand at end of life amounts to about 28 W, a 30 % improvement compared to ScaRaB. Finally, perturbing torques generated by the scanner are reduced to about a fourth of ScaRaB's, thanks to lower inertia of the rotor and lower angular accelerations required by the nearly harmonic scanning law.

5.3. Lifetime and reliability

Bringing the number of telescopes from four on ScaRaB to one on OPERA improves reliability dramatically, as mechanisms and all the more electronics can be downsized across the board. Since more than half of ScaRaB's parts have been eliminated, reliability is improved by a factor of about two. To maximise OPERA's lifetime without increasing costs, some parts used for ScaRaB and which are subject to wear - e.g. scan mechanism bearings or rotor slip rings - have been replaced by longer life parts (see § 3.4).

6. CONCLUSION

Here, we have presented a new instrument for earth radiation budget measurement at the top of the atmosphere in which spectral channels are multiplexed. This instrument, which provides more accurate data than previous instruments, is easier to accommodate on a spacecraft, especially small ones, and can be built for about half the cost. This ambitious cost objective could be fulfilled without increasing risks primarily by discarding as many ScaRaB parts as possible. The electronics in particular can be dramatically simplified and is the major source of savings.

In modifying the architecture of previous multi-telescope radiometers, likely leaps in technology, for instance in the field of superconducting bolometers, were born in mind in order to ease their future use for earth radiation budget measurement. Such new developments would upgrade radiometric precision further and open up new areas of investigation to scientists.

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