IR detectors for the GERB instrument on MSG

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ABSTRACT

The Geostationary Earth Radiation Budget (GERB) instrument is to be flown on ESA's Meteosat Second Generation (MSG) satellite in 2000. The purpose of the instrument is to measure accurately the daily cycle of the reflected and emitted radiation of the Earth over at least a five year period. The measurements will be made from geostationary orbit and will complement those planned from instruments in low Earth polar orbits. The data from GERB will provide the first consistent measurements of the hour-by-hour variation of clouds and simultaneous measurements of the radiation balance, and will allow climate models to be further developed and validated. The instrument will accumulate images of the Earth disc every 15 minutes in wavebands of 0.32 - 4.0 μm and 0.32 - 30 μm with a nadir resolution of 50 km. The detector for this instrument consists of a 256 pixel linear array of thermoelectric (TE) elements. The TE array operates at room temperature and is blacked to give a flat spectral response over the 0.32 - 30 μm band. The detector hybrid consists of the 256 pixel detector plus 4 Application Specific Integrated Circuits (ASICs), comprising 64 channels each, which perform front end analogue signal processing, A/D conversion and multiplexing. As the MSG platform is spin-stabilised, the Earth image is stabilised on the detector using a de-spin mirror and is only present on the detector for 40 ms. Integration of the signal over the 40 ms and taken over a 15 minute observation period enables the radiance in both long and short wavebands to be measured to an accuracy better than 1%. The detector concept is described and test results of a prototype system are presented.

Keywords: IR detectors, thermoelectric, gold black, EOS

1. INTRODUCTION

The Earth Radiation budget (ERB) is the balance between incoming radiation from the sun and outgoing reflected and scattered solar radiation and thermal radiation emitted. The ERB is the energy source for the climate system and therefore careful monitoring of the ERB aids in understanding the processes that govern the natural stability and variability of the climate system. Naturally occurring factors such as cloud cover affect the radiation budget. However these natural processes may be modified by man-made activities, such as global warming, and it is the extent of these modifications that is a major current concern of Earth Observation Scientists¹.

Previous ERB measurements have been made from low Earth orbit (LEO). The data obtained to date have been useful in validating models of the climate system. However these, and future missions planned, all have intrinsically poor time resolution, taking on the order of days in the case of drifting phase LEO to achieve full geographical coverage. They therefore cannot provide any information on important temporal variations such as the diurnal cycle and synoptic variability.

It is the purpose of GERB to take measurements of the ERB with a temporal resolution of 5 minutes, achieving full accuracy in 15 minutes. Data is gathered in the visible, short wave (SW), and infrared radiation, long wave (LW), bands, the SW radiation being a measure of the visible light from the Sun reflected off the Earth, while the LW radiation is the thermal radiation emitted by the Earth. From its position on the geostationary Meteosat Second Generation (MSG) satellite, stationed at 0° latitude and 0° longitude, the nadir spatial resolution of GERB is 50 km. This is lower than the resolution achieved from LEO. The limited coverage of the Earth achievable from geostationary orbit is also poorer than from LEO, however it is the temporal resolution of GERB which is its main advantage, taking a full data set to the necessary accuracy over the Earth's disc in 15 minutes.

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The main instrument on board MSG, the Spinning Enhanced Visible and Infrared Imager (SEVIRI) measures the radiation in 12 narrow wavebands. With its high spatial resolution of 3 km and time resolution also of 15 minutes, SEVIRI and GERB will provide complementary information enabling detailed studies of water vapour and cloud forcing.

The GERB instrument has been reported previously². Since then there have been significant project and design changes.

The University of Leicester (LU) is responsible for the development of the GERB detector subsystem, comprising the detector, signal conditioning electronics (SCE) and front end electronics (FEE), as shown in Figure 1. The detector, a 256 element thermoelectric (TE) linear array, is being developed by Honeywell Technology Center (HTC). It is the responsibility of LU to test the detectors and choose the flight device.

Figure 1 GERB detector subsystem

2. DESIGN CONCEPT

2.1 System Design

The system concept is to use a linear array of 256 thermoelectric pixels, which scans back and forth across the Earth's disc. The use of a blacked thermoelectric detector gives broad spectral coverage, covering the range 0.32 to 30 μm . The introduction of a quartz filter into the optical path blocks the IR radiation, allowing the visible radiation in the SW band of 0.32 to 4.0 μm to continue through to the detector. The LW radiation, 0.4 to 30 μm , is obtained by subtraction of the SW from the total radiation.

A complete image of the Earth in the total radiation band is gathered in one sweep, while the complete image in the SW is collected in the return sweep. A full picture of the Earth's disc in the 2 wavebands takes 5 minutes. To improve the signal to noise ratio, three complete scans are taken of the Earth, giving a data set of the ERB in 2 wavebands every 15 minutes.

As the satellite is rotating at 100 rpm, the GERB instrument possesses a de-spin mirror, counter-rotating at half the satellite speed, to stabilise the Earth's image on the detector. The Earth scene dwells on the detector for 40 ms during one rotation. The de-spin mirror is rotated at a speed slightly faster than half the satellite rotation so that on each rotation the detector looks at an adjacent slice of the Earth. In this way the detector effectively scans across the Earth's disc, until it reaches the end of the scan, when the de-spin mirror is set to rotate slightly slower than half the satellite speed and the detector scans back across the Earth.

During any one rotation the detector sees the inside of the spacecraft, a black body and a calibration monitor, as illustrated in Figure 2. The black body is set at a temperature of 20 $^{\circ}\text{C}$ above the Instrument Optical Unit (IOU) and is used to calibrate

the IR response of the detector. A zero reference point is also obtained by viewing deep space at the end of the Earth scan. The calibration monitor consists of an integrating sphere through which sunlight passes and which allows calibration of the visible response of the detector and monitors the degradation of the optics.

The detector and FEE are located in the IOU along with the telescope assembly, black body and calibration monitor, all of which have to be housed in a box of dimensions of the order of 0.4 m by 0.3 m by 0.3 m. One of the considerations therefore in instrument design is the size of the components and their optimum configuration to achieve their required performance within the limited space available.

Figure 2 Simulation of radiance reaching the GERB detector over one revolution

2.2 Detector Design

The 256 element linear array from HTC is a custom device and is based on the standard 128 element TE IR sensor. The standard linear array is used in commercially available hand-held IR cameras³. The detector operates at room temperature, eliminating the need for cooling equipment, which is expensive and requires space and power, both limited resources on board a satellite. The principle of operation is the thermoelectric effect, the same as that of a thermocouple. The thermoelectric effect arises when two dissimilar metals are joined forming two junctions. Radiation falls on the “hot” junction and the ensuing difference in temperature between the hot and cold junctions causes heat to flow, creating a voltage, which can then be measured directly. This measured voltage is directly proportional to the temperature difference, the responsivity of a particular detector being a measure of the voltage out for the amount of power in. A schematic diagram of one pixel from a typical TE array is shown in Figure 3. For these detectors, the junction connected to the silicon substrate does not respond to incident power, being effectively connected to a large thermal bath, while the other junction is suspended over a cavity on a silicon nitride microbridge and does respond. The microbridge provides good thermal isolation from the substrate, which manifests itself as high responsivity. The small thermal mass of the pixel results in a fast time response⁴.

Typical values of relevant parameters of the standard TE sensors are given in Table 1. The detector specification is also shown in Table 1. It can be seen from the table that the main developments and improvements to the existing detector design are in doubling the number of elements, halving the noise equivalent power (NEP) and increasing the spectral coverage.

Figure 3 Cross-section of a typical TE pixel

Parameter	Commercial Device	GERB Specification	Units
pixels	128	256	
operating temperature	room temperature	-10 to +40 °C	
pixel pitch	50	55	μm
pixel responsivity	265	400	V/W
pixel NEP	8×10^{-11}	4×10^{-11}	W rms
operating range		0 to 3×10^{-7}	W
linearity		$<8 \times 10^{-11}$	W
thermal time constant	12	10	ms
spectral response	8 - 12	0.32 - 30	μm
absorptivity	55%	0.3 - 10: >95% 10 - 20 μm : >90% 20 - 30 μm : >90%	

Table 1 Detector parameters: comparison between existing commercial devices and the GERB specification

In order to improve the spectral coverage, that is improve the absorption and hence response of the detector over the full required range, it is proposed to cover the detector with a gold black coating. As TE detectors respond to the total amount of energy absorbed (in contrast to photo-detectors which respond to numbers of quanta absorbed), the more radiation that is absorbed results in improved responsivity and hence sensitivity of the detector. The “blacker” a surface is the more radiation it absorbs. Applying for example black paint or “soot” to a surface are viable methods to obtain a reasonably black surface. The use of metal particulate coatings, such as platinum and gold, by electro-chemical deposition or evaporation, have been shown to produce good absorption over a wide spectral range⁵⁻⁶.

The thickness of the coating should be optimised for maximum absorption but balanced against minimum thermal mass: for the GERB detectors the optimum thickness is estimated to be 10 μm. Given that the pixel structure is of the order of 55 μm with 10 μm between pixels, a potential problem with the blacking is the possibility of the coating building up in the cavity underneath the pixel, effectively joining adjacent pixels and also shorting the electrical connections.

2.3 Electronics Design

The electronics is split into two separate sections: the SCE and the FEE, as shown in Figure 1. The SCE, comprising four Application Specific Integrated Circuits (ASICs), is situated as close as possible to the detector to minimise noise pick up in the connections. Each ASIC consists of 64 channels, one for each detector pixel, operating in parallel. Each channel comprises an amplifier, an over-sampling sigma-delta modulator, a 32 times decimation filter and an output serial interface. The sigma-delta (Σ - Δ) modulator operates at (spacecraft clock / 128 =) 29 kHz and with the 32 times decimation filter, this gives an output sample rate of 910 Hz, or 36 samples in one 40 ms observation period. The data from the four ASICs are then output on a single serial interface to the FEE.

The all-digital, digital signal processing (DSP) based, FEE, located on a separate card within the IOU, then processes the data by ordering it and applying two digital filters of the form

$$\lambda_1 \sin\left(\frac{\pi t}{T}\right) + \lambda_2 \sin\left(\frac{2\pi t}{T}\right)$$

to maximise the signal to noise ratio and compensate for the high frequency effects of the Σ - Δ modulator.

The resulting output from the FEE of 256 times 2 16-bit numbers per scene is then sent to the instrument Electronics Unit (IEU), where it is then telemetered to ground for processing into radiance.

As the response time of the detector is 10 ms it would take of the order of 100 ms for the detector to reach equilibrium, that is for the detector output to reach the final value of the scene. As there is only a 40 ms stabilisation period on the scene, the detector does not reach equilibrium and certainly does not reach the 0.5% accuracy required in the LW measurements. Assuming that the response is a single exponential (which has been shown to be a very good approximation by thermal modelling by HTC), the signal correlated with the two filters allows extraction of the true value to the accuracy required.

3. BREADBOARD TESTING

3.1 Breadboard Aims

The aims of the breadboard are to test the system design concept, to provide some measurements of noise and to highlight potential problems with the system. The breadboard was built to test the available standard 128 element TE arrays but can be readily upgraded for testing of flight detectors and electronics. Initial tests were concerned with reading the output from several pixels using off-the-shelf components to gain an appreciation of the detector behaviour and electronic requirements. Concentrating on one pixel's output, parameter measurements were taken to confirm the manufacturers values and establish testing methods.

3.2 Breadboard Set-up

The principle design of the breadboard uses a rotating turntable to simulate the rotation of the satellite. The set up is shown in Figure 4. A test image, of adjustable temperature, simulating the Earth, is positioned 3 m away from the focal point of a telescope arrangement, comprising a focussing mirror and a 45° turning mirror. At the focal point of the telescope is situated the detector. Between the turning mirror and the detector is a rotating turntable, whose speed of rotation can be adjusted. On the turntable is a series of baffles and mirrors, so that the detector 'sees' different scenes as it rotates. In any one revolution the detector sees a blackened baffle, at room temperature (simulating the inside of the spacecraft IOU), followed by a blackbody, then another baffle then the test image and a baffle again. The speed of rotation can be set at 100 rpm as on the satellite, but can also be adjusted allowing for observation of different aspects of the detector's response. The blackbody is a flat plate of copper painted with high emissivity black paint, whose temperature can be monitored and controlled.

Figure 4 Breadboard set-up

A temperature control box is capable of monitoring up to four temperatures from 100 Ω platinum resistance thermometers (PRTs): the test image, the black body, air temperature and the detector. The control box also controls the current to resistive heaters on the test image and black body, to maintain the temperatures set by the user from the computer software.

The detector is a 128 element standard TE array from Honeywell, with 50 μm pixel pitch and responsivity of 265 V/W, as given in Table 1. The detector has a germanium window covering the pixels, which contains a vacuum. The outputs from four pixels are sent through a series of amplifiers and an integrating amplifier to an Analogue to Digital Conversion (ADC) card in a personal computer (PC), which acquires and stores the data. An LU custom card controls the data collection sequencing and integration time, the user being able to set these from the PC keyboard.

3.3 Breadboard Results

Figure 5 shows the typical output from the breadboard system for one pixel for one revolution of the turntable. Comparing this with the simulation shown in Figure 2, it is immediately obvious that apart from the calibration monitor, the breadboard reproduces the radiation falling on the detector and detector response expected from the GERB instrument, albeit not to the same accuracy.

The noise of the breadboard system was calculated to be 5.2×10^{-10} W rms, which is considerably higher than required by specification of 9.1×10^{-11} W rms. However, in order to compare this with specification requires making some assumptions about the flight detectors and electronics performance and projecting the noise value. The flight detector will have a larger pixel area with larger absorption due to the blacking, as opposed to the reduced transmission of the germanium window on the standard detector. The breadboard electronics used are more noisy than the flight electronics, while the breadboard detector is also more noisy than the flight detector. Taking all these factors into account, the theoretical flight detector noise is then predicted to be 6.7×10^{-11} W rms, which is within the specification.

Figure 5 Detector output for one pixel for one revolution from breadboard tests

Measurements of the responsivity and time constant confirmed the manufacturer's values.

Drift was considered as a potential problem with the detector, both on the short term (over one revolution) and on the longer term. Drift over one revolution would introduce errors into the calibration of the signal, as it is the difference between the Earth signal input and the black body in one revolution that is measured. On longer time scales drift would be a problem if it continued in one direction and took the signal out of the electronics range. It was found however, that drift was not a problem.

4. DISCUSSION

The technical specification for GERB is a challenging one requiring careful consideration of the detector and electronics design. The choice of detector represents a compromise between established, commercially available technology and an extension of these capabilities to meet the new requirements.

The noise performance of existing commercial arrays has been experimentally demonstrated. The results of the breadboard tests yielded a noise figure which was approximately 5 times higher than that required for flight. An evaluation of the factors which impact on the noise in the flight system has been made resulting in an estimated noise performance for the flight detector design operated in the flight system of 6.7×10^{-11} W rms. The simple scaling of each of the system parameters from the breadboard to the flight case gives a high degree of confidence in the ability to meet the flight noise specification.

The optimisation of the use of a custom 256 element linear array for use in Earth observation has been described. Whilst the noise of the commercial detector and system is inadequate for the Earth Observation Scientists' requirements, careful consideration of performance parameters and system implementation has resulted in a measurement system which is close to the noise limit for the pixel element. The use of blacking, in this instance gold black, is vital to both increase the device responsivity, by a factor of almost 2, and to provide a flat spectral coverage over the 0.32 - 30 μm waveband.

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