GERB ROTATING MECHANISMS FOR MSG

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ABSTRACT

GERB (Geostationary Earth Radiation Budget experiment) is intended to make accurate measurements of the Earth Radiation Budget from geostationary orbit. It is mounted at the periphery of MSG that rotates at 100 rpm and consequently experiences a constant radial acceleration of 16g. GERB contains a rotating optical De-spin mechanism (DSM) that enables static registration of the Earth view, and a compact Quartz Filter Mechanism (QFM) which provides the instrument with both total and short wavelength measurements. Both mechanisms are mounted such that their axes of rotation are perpendicular to the radial acceleration.

This has a major impact on the DSM bearing lubrication configuration, which is required to survive constant running at 50 rpm for 92 million revolutions. In addition the control of the DSM rotation has a positional accuracy requirement of 65 μrads. The development and testing employed in identifying a successful solution to these unique problems is described.

The key features within the compact design of each mechanism are given, along with details concerning the implementation of soft pre-loading.

1. INTRODUCTION

GERB is an Announcement of Opportunity instrument to be flown on a MSG (Meteosat Second Generation) satellite, spinning east to west at 100 rpm in geostationary orbit. It measures the thermal infrared (IR) emitted from the Earth and the non-absorbed 'visible' sunlight (SW) reflected from Earth, uniquely providing 24 hours coverage. The principal design features of the instrument are summarised as follows:

- 3 mirror anastigmatic telescope
- Anti-polarisation fold mirror
- Wide band linear detector array
- Rotating scan mechanism
- Channel separation via quartz filter
- Black Body for thermal calibration
- Solar diffusing Calibration Monitor for short wave calibration
- Passive thermal design

The GERB instrument consists of two units plus the Inter-Unit Harness: the Instrument Optics Unit (IOU) and the Instrument Electronics Unit (IEU). The IOU measures 450mm x 200mm x 200mm and contains the imaging optics, detector system, DSM, QFM, on-board black body and the short wavelength calibration monitor. The IEU receives detector data, formats it and passes it on to the spacecraft data handling system. It also provides regulated power to all the subsystems, thermal control of the IOU, command and data interfaces and instrument health monitoring and control.

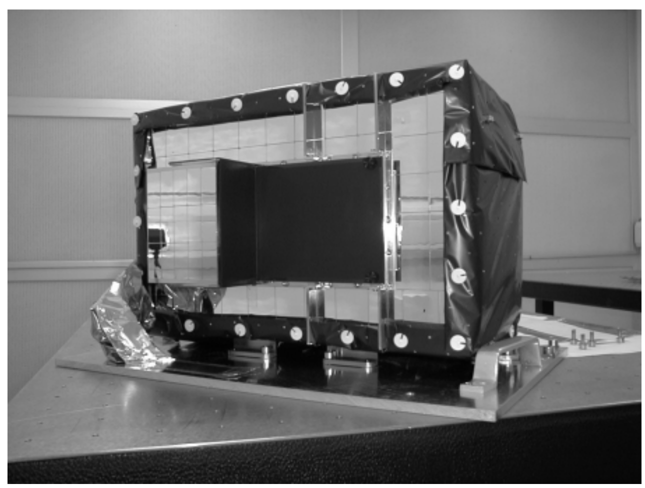

Figure 1. GERB IOU PFM

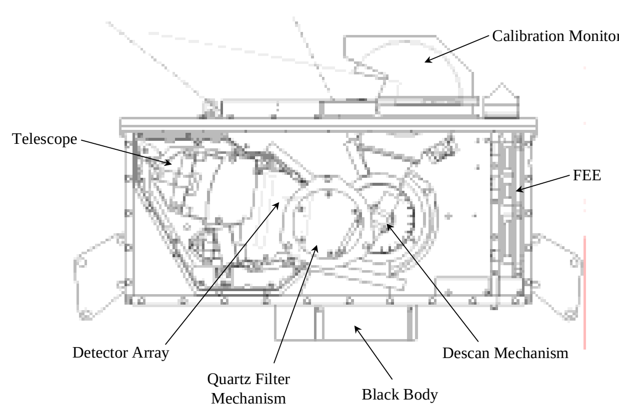

Figure 2. Plan view of GERB IOU

The configuration of the IOU is shown in Fig. 1 and 2. The IOU views the Earth with a black wide-band detector array, providing measurements of the Earth's output radiation in a total band 0.32µm - 30µm, and a short wave band 0.32µm - 4.0µm. A long wave band, 4.0µm - 30µm, is obtained by subtraction. A quartz filter placed in and out of the beam at the front of the telescope provides the switching between bands. In order for the detectors to obtain sufficient signal to meet the signal-to-noise requirement during each 15 minute MSG product, and to accommodate GERB on the spinning MSG platform, GERB provides a de-spin mirror to increase the length of available exposure per spin.

From MSG the face of the Earth is viewed by a 1 x 256 pixel detector array via the despin mirror, the 3 - mirror anastigmatic telescope and an anti-polarisation fold mirror. The telescope is designed to enable the detector array to view the full 18° north-south field of view of the Earth. Full coverage of the Earth is achieved by adjusting the phase of the DSM so that each image consists of a series of consecutive strips in the north-south direction.

The same telescope and detector are used to make measurements in the two spectral bands. The required longwave measurement is obtained by subtraction during ground processing. This dual use of telescope and detector implies physical co-registration between bands but individual measurements cannot be made temporally coincident. Two complete spectral images of Earth are produced every 300 seconds. This data is averaged together to produce a 15 minute image during ground processing.

The telescope views the Earth or calibration sources from the DSM which scans past the aperture of the optics unit, in the direction counter to the spacecraft spin and at half the spacecraft rate. This motion effectively produces a shuttered frozen Earth view for a fraction of the satellite rotation period 600msec. The detector collects data when viewing the Earth, Calibration Monitor and Black Body, in sequence, each revolution of the spacecraft. The data capture period for each source is 40 msec.

Direct sunlight will damage the detector and so protection mechanisms are incorporated into the GERB design.

2. QFM DESIGN IMPLEMENTATION

The Quartz Filter Mechanism is a compact, insertion mechanism which performs the switch between total and short wavelength measurement This is implemented by rotating a filter holding turn-table through the optical path between the de-spinning mirror and the telescope.

Late in the design phase, when the available envelope volume had been defined, the filter mechanism was also required to perform a shutter function.

Because of the limited available volume, a novel two-piece shutter solution was implemented.

In this configuration the filter mechanism can operate three stations: filtering, shut, open (see Fig. 3). By rotating in only one direction the drive is greatly simplified.

Figure 3. Filter Turn-Table Stations

The shutter function is required in-orbit, to avoid the detector viewing direct sun radiation which would cause catastrophic failure of some pixels.

Sun illumination can occur during early orbit phases, when GERB is unpowered and not synchronised to the MSG spin, and near eclipse conditions. The holding of the shut position is achieved by a motor detent torque greater than 40 mNm and by an additional 20 mNm holding magnet torque.

Discussions concerning the stepper motor detent torque were held, with the motor manufacturer Etel, early in the mechanism design. No guarantees could be made however of achieving the minimum holding torque requirement so a secondary system was required. Extremely tight packaging requirements on the QFM, and other surrounding sub-systems, denied the opportunity of locating a separate launch lock mechanism. Accurate design and evaluation of the magnet holding torque has been experimentally performed on a dedicated magnet rig. The Samarium Cobalt magnet solution selected for the final design combines simplicity with a small volume due to the high-energy product of the magnet material. Development of this system was necessary to ensure the correct magnet geometry, position and air gap was chosen to counteract the maximum torque that would be generated by launch loads on the balanced rotor. Tests showed that the final design achieved a torque safety margin of ten.

Key to minimising the holding torque is accurate balancing of the rotating components. This is achieved through design analysis and by fine adjustment, to less than 0.1 gmcm, during dynamic balancing.

The rotating equipment consists of a titanium alloy shaft (see Fig. 4) to whose end the filter turn-table, with balancing flange, is mounted.

Figure 4. QFM Rotating Equipment

The filter is a 1.5 mm thick Suprasil synthetic quartz slab, softly bonded by urethane adhesive into an aluminium frame. It is also very lightly clamped at either end to provide additional positional security. In spite of this retention method a 0.2 fringe error in transmission is achieved.
On the other end of the shaft the stepper motor rotor and a second balancing flange are mounted.
In order to assure the required motor performance, the manufacturer requires a coaxiality of 0.010 mm between rotor shaft and stator housing (and hence very tight tolerances in the chain between the rotor shaft and the stator housing).
The rotating equipment is supported by a pair of 24 mm outer diameter angular contact ball bearings, dry lubricated by ion plated lead on the races, with minimum mass leaded bronze cages. The bearings are back to back mounted with a 50 N compliant preload applied by a helical spring which is constrained by the outer race of the lower bearing. Even under the continuous centrifugal 16g environment, no accelerated life test or special cage to reduce wear debris were deemed necessary, due to the low required duty cycle (less than 1 million single direction intermittent revolutions).
To match thermal expansion between bearings and their seats on the housing and to reduce mass, a bimetallic solution was selected for the housing. A slim hardened stainless steel cylinder, in which the bearings are fitted, is structurally bonded to an aluminium cylindrical body, housing the motor stator.
The bearing seat near the filter holder is sputtered with MoS_2 to ease possible motion of the sliding bearing during life under the elastic preload.
The view of the QFM flight model is shown in Fig. 5. The mechanism is mounted on the outside face of the instrument top plate and projects throught the plate into the instrument allowing compact integration in the limited available space.

Figure 5. Quartz Filter Mechanism

The rotating equipment is driven by a 200 step motor in open loop control. The position is monitored by three Hall effect sensors (HES) activated by a single magnet. During operation it is key that each turntable position is acquired accurately. Samarium Cobalt magnets on the rotating shaft pass HES attached to a PCB that is mounted on the housing. Development of this system was conducted using a simple rig that allowed the angular sensitivity to be measured. The particular latching HES used is activated by the presence of a south pole, but benefits from the containment of the magnetic field through adjacent mounting of north poles on either side. The radius of the HES from the axis of rotation, and the air gap between the HES and magnets were varied. Results indicated using the short radius arm that small movements in HES radial position had no effect on angular sensitivity. To balance the ease of assembly with switching performance the optimum air gap was found to be 0.5mm.

3. DSM DESIGN IMPLEMENTATION

The De-Spin Mechanism, DSM, shown in Fig. 6, is a plane double sided mirror mechanism counter-spinning at 50 rpm in the opposite sense of the 100 rpm spinning spacecraft. The mechanism is driven by a synchronous, two-phase, high output motor with positional feedback provided by an Inductosyn rotary transducer. During its scan, the DSM reflects the incoming light beam into the instrument telescope and, hence, generates one 40 msec stationary image of the Earth for each revolution of the spacecraft.

Figure 6. De-Spin Mechanism

The mirror must also rotate to allow a calibration sequence to be performed by viewing a black body and a Calibration Monitor at defined intervals within the scan cycle.
The planned life for DSM is in excess of 3.5 years continuously rotating at 50 rpm (i.e. 115 million revolutions, taking into account design safety margins) under a constant radial acceleration of 16 g.

Fig. 7 illustrates the rotating components in the DSM. The mirror is an 18mm thick, 56 mm high, 76 mm wide, aluminium alloy part, which contributes to positioning the CoG of the rotating equipment equally between the supports of the shaft. The flatness is 0.1 fringes and microroughness better than 2 nm_{RMS}. The mirror faces are finished with an enhanced reflective silver-based coating.
Below the mirror a wide titanium flange acts as a labyrinth cover against wear debris, a balancing flange and also a moving axial stop.
On the opposite end are shown the motor rotor, the lower balancing flange, and the rotary transducer rotor.

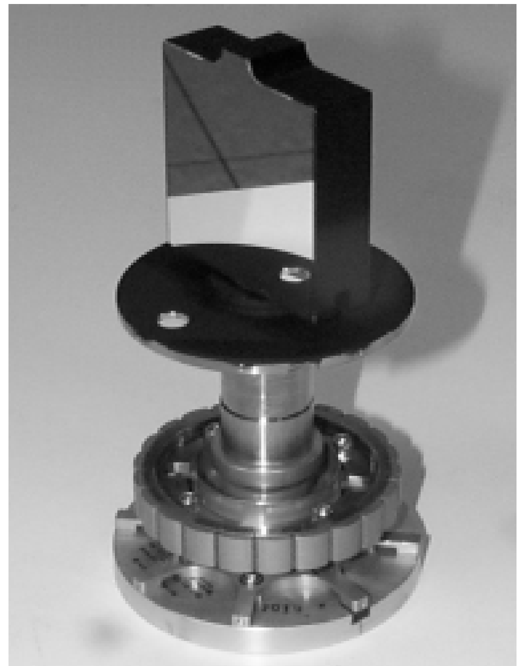

Figure 7. DSM Rotating Components

Between the ends of the shaft a pair of angular contact bearings with 47 mm outer diam and high conformity races (1.08) are mounted and softly preloaded.

The bearings are commercial items whose ball complement has been reduced from 13 to 9. The purpose designed hybid cage is made of VESPEL SP3 with inserts of leaded bronze, required to resupply the ion plated lead lubricant on the races.
To match the bearing seats the aluminium alloy housing is lined with hardened stainless steel to avoid CTE mismatching.
From the start of the mechanism design, life under a constant radial acceleration of 16 g was understood to be the most demanding and most critical requirement for the mechanism and, in particular, for its ball bearings. No proven solution existed for such an operating environment.
Due to the proximity of optical surfaces dry bearing lubrication was the preferred option. Not only the life of the dry-lubricant film (the selected ion plated lead, as used for many years in European space applications and in 1 g conditions, has performed > 10^9 revs in ground vacuum tests), but the wear of bearing cages and location of wear products was identified as a major challenge and concern.
Due to the unusual friction and wear issues the necessity to test in vacuum on a purpose built centrifuge (Fig. 8) to simulate the spacecraft environment was deemed mandatory.

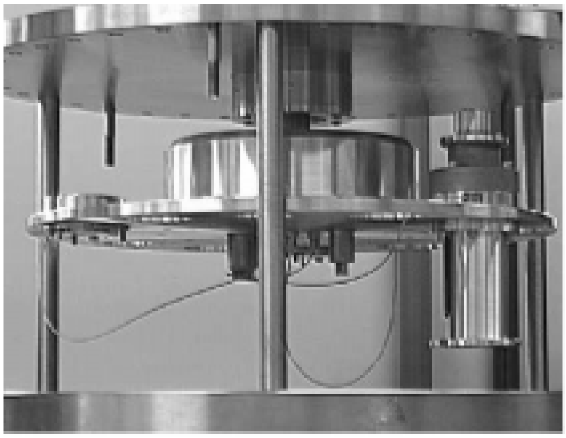

Figure 8. Lifetest Centrifuge at ESTL

From results of vacuum centrifuge accelerated lifetests, performed in the facilities of European Space Tribology Laboratory, a hybrid cage bearing option, shown in Fig. 9, with ion plated lead lubricant, was selected. This configuration out-performed and out-lived two other options, however the test prematurely stopped after the equivalent of 2.5 years (see ref 1 for more extensive information).

Figure 9. DSM Hybrid Cage

The stoppage of the DSM life test model was caused by wear debris choking the bearing. Insufficient debris capture volumes surrounding the bearings caused the bearing to jam.

The generation of debris was somewhat higher and much more concentrated across a small arc of the bearing seat than was expected.

Following cessation of the test, examination of the bearings indicated that the lubricant and bearing elements were still in good tribological condition.

The wear of both cages was measured. Results from the cage with the greatest wear were then extrapolated to indicate the expected wear after 7 years of in-orbit life. This analysis projected that a minimum volume of 245 mm^3 would be required over 30° either side of the direction of aceleration.

However it was possible to incorporate capture volume traps (see Fig. 10), aligned with the direction of the centrifugal acceleration , of 1700 mm^3, i.e. ~7 times greater than the required extrapolated volume.

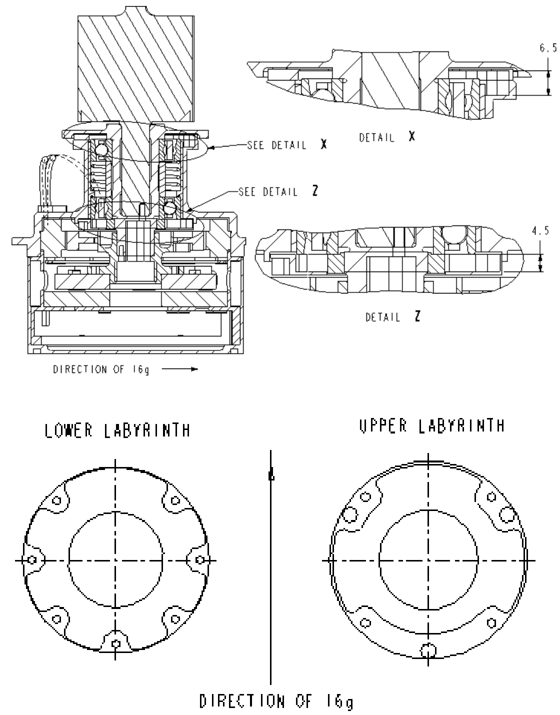

Figure 10. DSM Capture Volume Traps

Motion accuracy requirements were another key requirement which had a strong impact on the tolerarances of the mechanical design. The nature of the double-sided mirror combined with the technique of pixel subtraction for the long wavelength measurements, demands an accurate and repeatable system. This is illustrated in the specification for mirror Wobble (650 urads) and Wobble Repeatability (28 urads).

Measurements of wobble have exceeded the requirements even though the sliding bearing bore had to be increased by 10 µm, in comparison to the manufacturer's guidelines, to ensure the correct pre-load performance.

Similar to the QFM, the dynamic balance of the rotating part of the mechanism was required to be better than 0.2 gmcm, to reduce disturbances of the instrument to a minimum. An even lower value (0.1 gmcm) was easily achieved by the means of a fine dynamic balancing set-up.

No launch locking was provided for the bearings. The only mechanical protection are three pin stops fitted in the housing. These impinge on the upper balancing flange during launch to prevent impacts between the separate Inductosyn parts, and assure a 0.1 mm gap.

3.1 Motor and encoder selection

Several designs were considered for the DSM motor. A brushless torque motor produced by ETEL was selected as offering the best combination of drive torque, low detent torque and geometry.

Mechanisms of this type have traditionally used optical encoders for position control. These have several drawbacks, including fragility, very precise alignment and can possible fail due to the ingress of bearing debris obscuring the optical sensor. Predicting that the GERB mechanism was likely to develop significant amount of debris an Inductosyn rotary encoder, produced by Farrand, was selected. These devices are rugged, high resolution and are not susceptible to debris contamination.

3.2 Control System

The control system is required to drive the DSM at a constant speed of rotation during the Earth view. The specification is in terms of Jitter (short term speed variations), 65 μrads, and Repeatability (ensures the same strip image is viewed on successive scans), 28 μrads over 15 minutes.

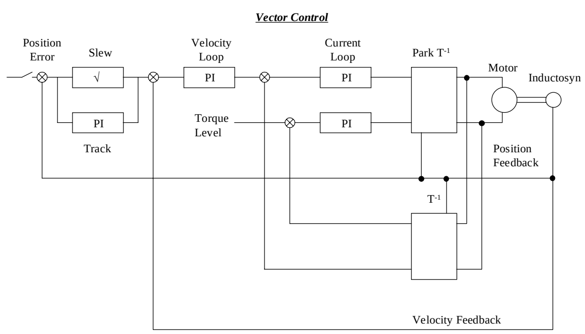

Figure 11. Block Diagram of DSM Control

The control system has to remain within specification as bearing friction varies not only between on ground and in orbit, due to the 16g, but also with life as the bearings wear and create debris. To accommodate this the torque level available to the motor is programmable from the ground up to a level of 300 mNm. A block diagram of the system can be seen in Fig. 11.

4. TESTING

During the development phase of GERB all subsystems were fully qualified before integration into the instrument. In addition the instrument has now been fully qualified and calibrated as a unit. No failures or anomalies were encountered with any of the systems including the mechanisms.

The flight instrument has been subjected to a 30 day calibration period in a purpose built facility at Imperial College of Science Technology and Medicine. During this period a full radiometric calibration was carried out using calibrated hot and cold black bodies and a visible source. The instrument was under vacuum for the 30 day period and the DSM was running for a large proportion of this time.

5. CURRENT STATUS

The flight model of GERB was delivered to the MSG prime contractor, Alcatel, in June 1999, and is due to be launched on MSG 1 in October 2000.The second round of bearing tests are due to start in September 1999.

6. CONCLUSION

The constant acceleration environment is peculiar to the GERB instrument. It was recognised from an early stage that the lubrication of the bearing would be a challenging task as there was no available test data under these conditions. Some assumptions based on analysis and experience proved to be correct, e.g. accelerated cage wear, however not all options studied proved successful e.g. cageless bearings. Initial 1g development testing suggested that cageless bearings offered the best solution. The lesson learnt here is that testing under simulated in-orbit conditions, in this case the centrifuge tests, proved to be the only reliable source of data.

The working partnership between OG and RAL has proved to be very successful, although RAL were responsible for the design, the very close involvement of OG in this process, both at conceptual and detail design phases proved to be invaluable. Serious Phase C/D problems can be avoided if the manufacturers are involved in the design process.

The very high scientific value of the GERB data has been promoted by the scientific community which, combined with the successful GERB1 programme, has resulted in GERB instruments being accepted for inclusion in the scientific payload of MSG2 and 3.

The mechanisms for GERB were developed under contracts from the Italian Space Agency (ASI) and the UK Natural Environment Research Council (NERC).

7. REFERENCES

1. Fabbrizzi, F., Sawyer, E., Gill, S., "Life Test Development and Results for the GERB Mirror De-Spinning Mechanism", *33rd Aerospace Mechanism Symposium*, NASA/CP-1999-209259 (May 1999).