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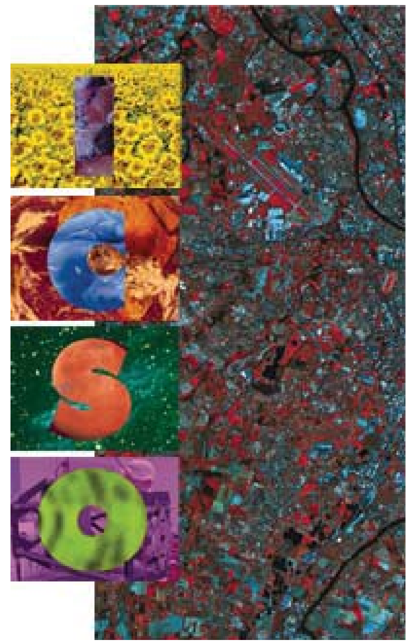

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DEVELOPMENT OF A THREE-MIRROR ANASTIGMAT TELESCOPE FOR THE GERB EXPERIMENT

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RESUME : L'expérience GERB, embarquée sur Météosat Seconde Génération, a pour but d'analyser le bilan radiatif terrestre dans un large domaine spectral (0.32 -30µm). Cet article décrit le développement du système imageur de GERB, un télescope anastigmat à 3 miroirs, ouvert à f/2 et visualisant un champ rectangulaire de 18° x 0.28°. Le télescope est entièrement réalisé en alliage d'aluminium et comprend un miroir primaire elliptique hors d'axe et deux miroirs sphériques ; la dimension maximale des miroirs est de 100 mm. Après intégration et tests environnementaux, la performance globale sur axe du télescope en termes de qualité optique atteignait 0,45 λ rms à 633 nm, à comparer à la valeur de 0,27λ rms résiduelle de la conception optique. L'analyse de tolérances optomécaniques de la phase de conception a débouché sur la définition d'une séquence d'intégration permettant de garantir la précision d'alignement de chaque miroir, nécessaire à la qualité image globale du télescope.

***ABSTRACT** : The GERB experiment, on-board Meteosat Second Generation, aims at monitoring the Earth radiation budget within a broad spectral range (0.32 –30 µm). This paper outlines the development of the GERB imaging subsystem, a f/2 three-mirror anastigmat telescope with a 18° x 0,28° rectangular field-of-view. The telescope is an all-aluminium design, comprising a primary off-axis elliptical mirror and two spherical ones, with a largest size of 100 mm. After integration and environmental testing, its global on-axis imaging performance reached 0,45 λ rms at 633 nm for an optical design value of 0,27 λ rms. The global opto-mechanical tolerance analysis of the design phase defined an integration sequence able to keep the individual alignment of each mirror within the accuracy needed to ascertain the whole telescope quality.*

1. INTRODUCTION

Understanding the behaviour of the Earth climate is one of the most important scientific problems to date that man has to face.
The point is to gain a deeper insight into the processes that control the climate system variability and global balance as well as to assess the consequences of man's activities.
Satellite-borne equipment is particularly well suited to collect relevant global data in numerous complementary fields and to exploit the associated synergy.
In particular, the GERB (Geostationary Earth Radiation Budget) experiment is to fly on MSG (Meteosat Second Generation) satellite and aims at measuring the balance between the incoming radiation from the sun and the outgoing reflected and scattered solar radiation plus the thermal infrared emission to space.
The geostationary orbit allows to get a very good temporal sampling of important diurnal processes affecting clouds and water vapour and brings a perfect complement to polar orbiting measurements.

The GERB radiometer will provide data for the region of the globe covered by MSG.
Short-wave (0.32-4 µm) and total (0.32-30 µm) measurements will be performed, the long-wave (4-30 µm) data being obtained by subtraction.

The GERB instrument is divided into three subsystems:

- the Instrument Optics Unit (IOU) comprising the optics, the detector and the calibration sources.
- the Instrument Electronics Unit (IEU) for data handling, power supply and thermal control.
- the Mechanisms Control Electronics (MCE) for quartz filter and despin mirror

The instrument characteristics are:

Platform	MSG	Geostationary Spin-stabilised (100 rpm)
Spectral bands	Short-wave	0.32 µm - 4 µm
	long -wave	4 µm - 30 µm (by subtraction)
	total	0.32 µm - 30 µm
Short-wave filter	quartz	
Accuracy	short-wave	1 %
	long-wave	0.5 %
Field of view (pixel size)	44.6 x 39.3 km	at nadir (NS x EW)

Telescope	3-mirror anastigmat	
	+ 1 fold mirror	to minimise polarisation effects
	+ 1 descan mirror	to remove the satellite rotation
Detector	256 x 1 thermal	linear array in North-South direction
Calibration sources	thermal infrared solar	blackbody integrating sphere
Sampling time	300 seconds	full Earth disc, both channels
Mass	25 kg	
Thermal Control	18°C - 22°C	at telescope level

The GERB instrument is produced by a European Consortium led by the UK, with the involvement of Belgium and Italy.

UK

- *Rutherford Appleton Laboratory (RAL)*
  main contractor
- *Imperial College (ICSTM*)
  science and calibration
- *Leicester University*
  detector and signal conditioning electronics
- *Hadley Centre*
  science

Belgium

- *RMIB*
  fluxes, near real-time data products
- *AMOS/OIP*
  telescope assembly

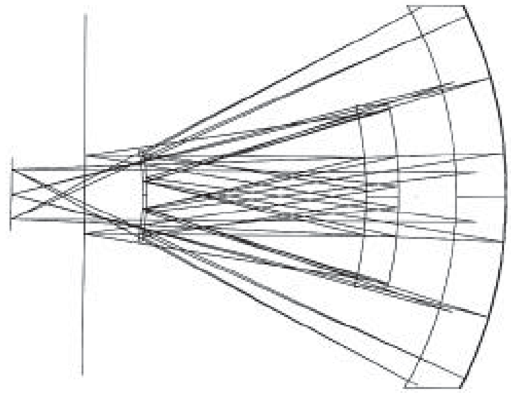
Italy

- *Officine Galileo*
  descan mechanism / quartz filter mechanism

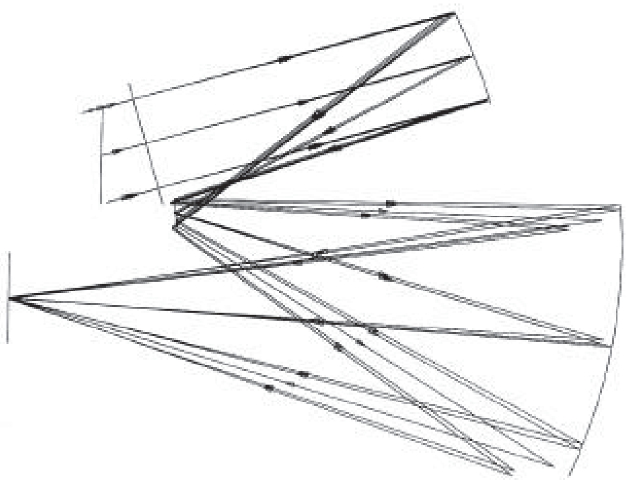
2. GERB TELESCOPE DESIGN REQUIREMENTS

The imaging subsystem of GERB is a three-mirror anastigmat (TMA) telescope.
The all-reflective design is well adapted to the broad useful instrument waveband.
The requirements were:

- ♦ optical configuration (see fig. 2.1.)



North- South View



East-West view

Fig. 2.1. GERB TMA Optical Design

entrance aperture stop :	- size 20.6 mm x 20.6 mm (f-number : f/2)
mirror M1 (PM)	- off-axis concave ellipsoidal (parent shape: prolate ellipsoid) - rectangular sizes: 57 mm x 30 mm
mirror M2 (SM)	- convex spherical - rectangular sizes: 30 mm x 11 mm
mirror M3 (TM)	- concave spherical - rectangular sizes: 106 mm x 74 mm
field-of-view :	- 18° x 0.28° (North-South bands on Earth disc)

♦ global imaging performance :

RMS telescope wavefront error in waves (λ = 633 nm)

	design	as-built	in-flight
on-axis	0.27 λ	0.57 λ	0.77 λ
in-field (edge of the FOV)	0.44 λ	0.80 λ	1.00 λ

The design values are obtained after design optimisation. As-built values include contributions of manufacturing and alignment.
In-flight values represent the performance awaited from the telescope after launch, encompassing effects such as launch vibrations, thermal cycling and centripetal loads due to satellite spinning.

♦ straylight performance

The straylight is controlled by telescope baffling performed by RAL and by minimising the mirror surface roughness

- for spherical mirrors : R_q < 2.7 nm RMS
- for aspherical mirrors : R_q < 5 nm RMS

Mirror cosmetic quality is imposed to be 60-10.
Contamination control : - particulate contamination level < 550 ppm
- molecular contamination level < 10^{-7} g/cm^2

♦ mirror reflectivity : UV- enhanced protected silver coating
♦ telescope focal length : 1% tolerance with respect to nominal design
♦ boresight error : <70µm
♦ telescope interface with optical bench : 0,2 % tolerance on mirror locations with respect to nominal design
♦ mass budget : 2 kg
♦ environmental requirements :
- thermal requirement :

Telescope mode	Operating		Non operating	
Telescope temperature	18°C	22°C	- 30°C	50°C

- launch environment : sine and random (15 g RMS) vibrations
- centripetal loading
The GERB instrument being located at 1,5 m from the satellite rotation axis (100 rpm) it will undergo a permanent centripetal acceleration of nearly 17 g.

3. OPTO-MECHANICAL TOLERANCE ANALYSIS

The opto-mechanical tolerance analysis was performed with the purpose of establishing the specifications on individual components (mirrors and mounts) which enable the telescope to reach the system performance.
The analysis was further split into ground as-built and in-flight (launch and in-orbit environment) performance by separating the contributors to each working case.
The system performance was essentially represented by the telescope wavefront error (on-axis and in-field values) which had the major impact on GERB radiometric accuracy. A parallel analysis was also made for telescope focal length and boresight error.
By means of a global ray tracing model, inverse sensitivity tables were established between the telescope wavefront error and the identified components parameters. The following table summarise the set of accounted contributors for as-built (table 3.1) and in-flight (table 3.2) cases.

Parameter	PM	SM	TM
curvature radius	x	x	x
conic constant	x	-	-
surface accuracy	x	x	x
Z local alignment (axial)	x	x	x
Y local decenter	x	x	x
X local decenter	x	x	x
α tilt (around local X axis)	x	-	-
β tilt (around local Y axis)	x	-	-
Total :	18 contributors		

Table 3.1 : Contributors identification table for As-Built WFE tolerancing

Parameter	PM	SM	TM
surface deformation	x	x	x
Z local alignment (axial)	x	x	x
Y local decenter	x	x	x
X local decenter	x	x	x
α tilt (around local X axis)	x	x	x
β tilt (around local Y axis)	x	x	x
γ tilt (around local Z axis)	x	x	x
Total :	21 contributors		

Table 3.2 : Contributors identification table for In-Flight WFE tolerancing

The next step was to build a preliminary tolerance budget based on the inverse sensibility table and on the actual capabilities in terms of manufacturing, integration and alignment of the telescope.

In the same way, constraints were put on the mirror design in order to take into account the feedback from the tolerance analysis.
Due to the inherent asymmetry of three-mirror telescopes, a statistical approach for combining the tolerance parameters is required.
The parameters can then be considered as random variables with a defined density of probability. In this way, it is possible to determine the probability to stay below a given wavefront error after telescope integration and alignment.
We took another approach, based on a worst-case analysis for both on-axis and in-field configurations. This worst case was tracked through an iterative procedure that attributed different values to the set of parameters within the defined tolerance range and looked for the maximum telescope wavefront error.
We also considered compensation mechanisms, based on one part on telescope refocusing at the detector level and, on the other part, on adjustment of mirror interdistance.
The final tolerance budget was tuned from the results of this analysis in order to stay within the required system performance.
The following table (table 3.3) provides an overview of the typical tolerances for the as-built performance:

Parameter	**Tolerance**		
	PM	**SM**	**TM**
radius of curvature	0,1 %	0,1 %	0,05 %
conic constant	0,3 %	-	-
decenter	10 µm	10 µm	10 µm
tilt	10 arcsec	-	-
RMS surface accuracy (at 633 nm)	λ/8	λ/10	λ/30

Table 3.3. TMA Tolerancing overview

4. DESIGN OF MIRROR UNITS

The concept of mirror units was selected on the basis of the manufacturing and integration plans. An all-aluminium design was retained to minimize the thermal gradients across the telescope. The mirrors were designed with integral mounts; the mounting strain path was isolated from the mirror surface by a slot located between the latter and the mounting screws, which allowed the created pad to play the role of a flexural spring.
The mirrors units were calculated to resist to the launch loads (mirror-mount assembly) and to the centripetal loading in operation (minimization of the surface tilt and deformation). Mirrors were manufactured using the diamond turning technology that also allowed to machine flat and coplanar mounting interfaces to the same tolerances as the optical surface figure.

The mirror manufacturing sequence was the following:

- rough machining of aluminium alloy (6061-T6) blank
- stabilisation heat treatment (temperature ageing)
- diamond turning of optical and reference surfaces
- optical testing
- stabilisation heat treatment (temperature ageing)
- optical testing
- electroless nickel plating
- stabilisation heat treatment
- optical figuring to required accuracy and required roughness
- optical testing
- protected silver coating application

5. TELESCOPE INTEGRATION AND ALIGNMENT

The first integration step consisted in assembling mirror and mounts (for PM and TM) and in checking afterwards the optical quality. A tightening torque in adequacy with the launch vibration levels was applied to the mounting screws. This operation affected somewhat the surface figure of TM which remained nevertheless compatible with the allocated budget.
The second step consisted in integrating the mirror units on their support baseplate. Due to the high accuracy needed, all the procedure was performed on the marble of a 3D coordinate measuring machine (CMM), installed in the cleanroom. The CMM constituted the reference frame for the telescope alignment and allowed to catch the locations of PM foci and SM and TM centers of curvature. The procedure began with the integration of the elliptical primary mirror on the baseplate: the beam emitted by the interferometer was focused on the first focus of the ellipsoid and reflected back on a ball placed at the second focus, after having hit the mirror (see fig. 5.1.)

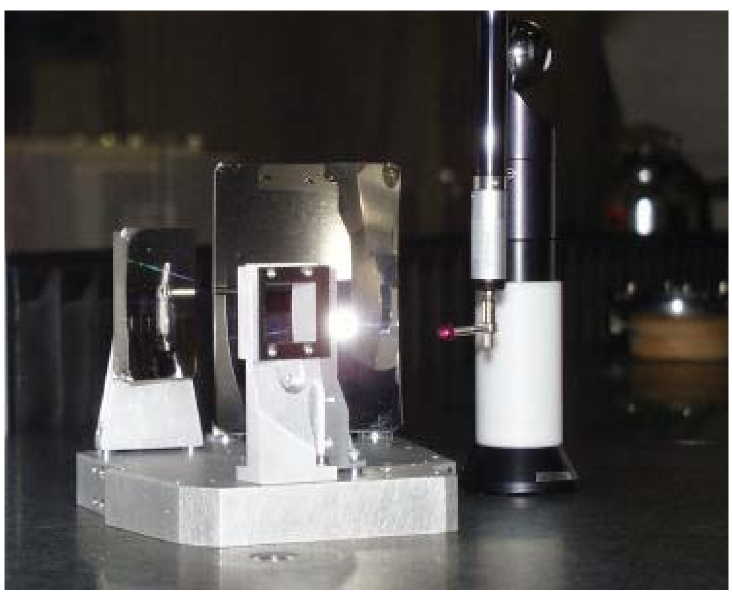


Figure 5.1. Telescope during integration

This step was the most critical of the alignment and required five independent adjustment possibilities on the mirror (three translations and two rotations), realised by lapping of washers at the interface between the mount and the baseplate.
Once the primary mirror integration was completed, the residual position errors with respect to baseplate were recorded, so that the nominal positions of SM and TM were corrected accordingly. PM orientation therefore fixed the whole telescope orientation (at less than 1 arcmin of the nominal one).
SM and TM were then integrated on the basis of the corrected coordinates using the interferometer focused on the centres of curvature and in autocollimation on the mirrors. Lapping of washers at the interface between mount and baseplate allowed to complete integration. (see fig. 5.2).
Since the whole procedure was performed within the accuracy requirements for individual components, the global specification for the telescope was reached without having to make use of the computer model to find the optimized compensating adjustments.

The results of alignment were:

	As-built specification (wavefront) λ = 633 nm	**Test (wavefront) λ = 633 nm**
on-axis	0,57 λ RMS	0,45 λ RMS
in-field	0,80 λ RMS	0,69 λ RMS

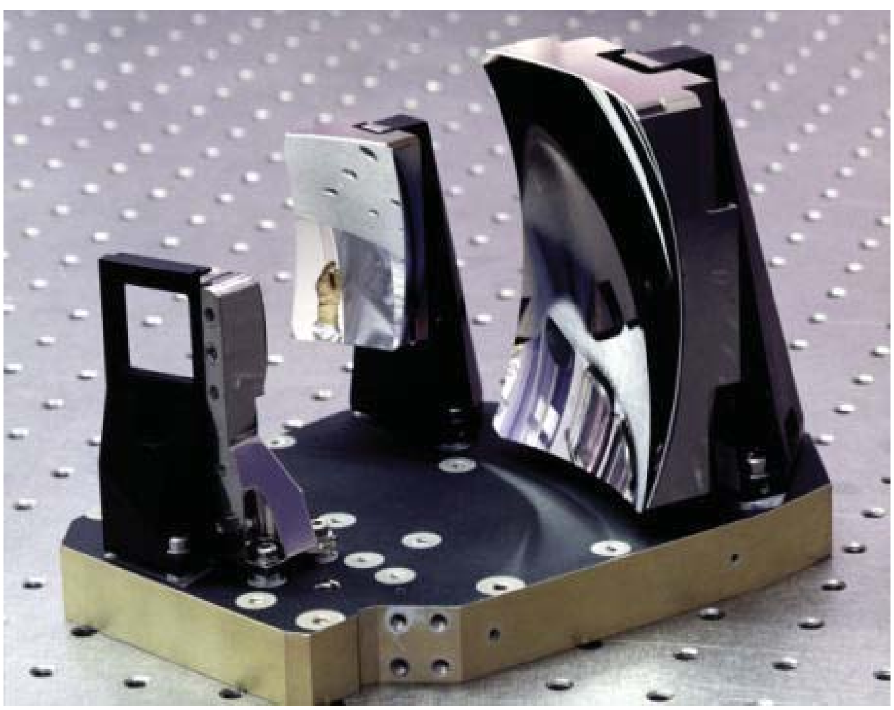


Fig. 5.2. Telescope at the end of integration

6. TELESCOPE TESTING

The telescope underwent thermal cycling (from –30°C to +50°C) and vibration testing (see fig. 6.1).

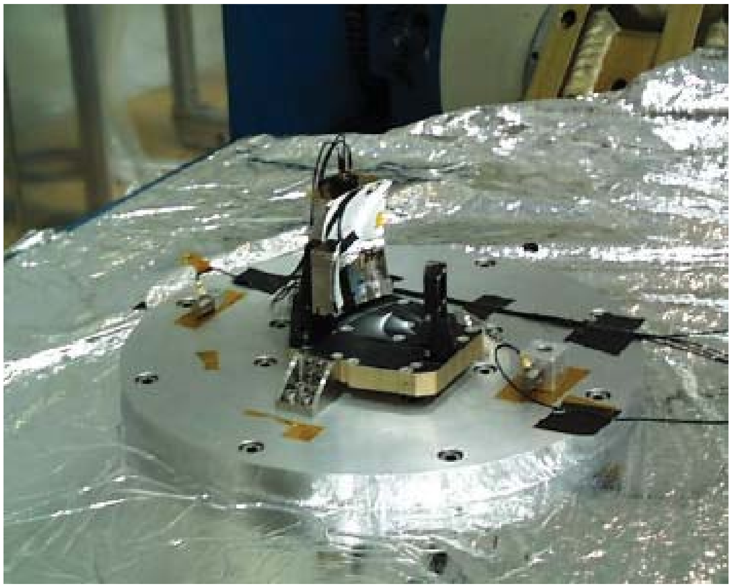


Fig. 6.1. Telescope on the shaker

There was no impact on the telescope wavefront error, while a best focus shift of 30µm was measured.
Introducing the effect of centripetal loading on the telescope quality, the final status was :

	In-flight specification wavefront λ = 633 nm	Test + centripetal loading
on-axis	0,77 λ RMS	0,60 λ RMS
in-field	1,0 λ RMS	0,80 λ RMS

7. CONCLUSIONS

The design and development of an all-aluminium three-mirror anastigmat for the GERB experiment has been presented.
From the opto-mechanical tolerance analysis, a dedicated alignment procedure was defined, involving interferometry combined with accurate metrology performed on a 3D coordinate measuring machine.

8. ACKNOWLEDGEMENT

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