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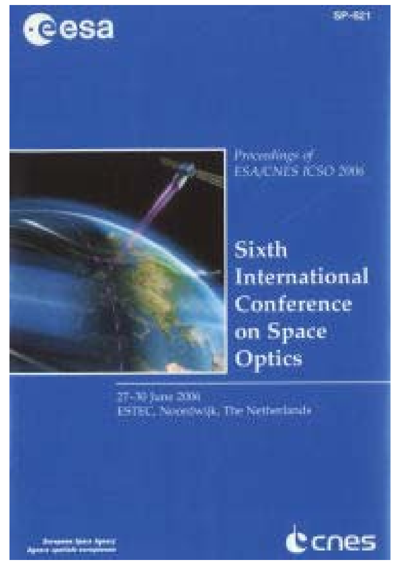

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COROT TELESCOPE (COROTEL)

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ABSTRACT

COROTEL is the telescope of the COROT satellite which aims at measuring stellar flux variations very accurately. To perform this mission, COROTEL has to be very well protected against straylight (from Sun and Earth) and must be very stable with time.
Thanks to its high experience in this field, Alcatel Alenia Space has proposed, manufactured and tested an original telescope concept associated with a high baffling performance. Since its delivery to LAM (Laboratoire d'Astrophysique de Marseille, CNRS) the telescope has passed successfully the qualification tests at instrument level performed by CNES. Now, the instrument is mounted on a Proteus platform and should be launched end of 2006. The satellite should bring to scientific community for the first time precious data coming from stars and their possible companions.

1. MISSION DRIVERS

1.1. Overview

The satellite will be pointed towards fixed areas in the sky (each containing more than 12 000 target stars) for periods of at least 5 months. Twice a year, the satellite will be turned back to keep the sun behind the entrance of the telescope. During these 5 months period, the telescope shall give very stable images of the target stars inside the field of view (2.7°x3.05°). This stability is of prime importance regarding the requirements coming from the two objectives : stellar seismology and exoplanet detection. Indeed, to succeed in these both missions, the telescope shall be able to measure star signal fluctuations around 10^{-6} over hundreds of minutes and 10^{-4} over 150 days in a low earth orbit environment. Thus the following criteria are the main drivers for the instrument :

- Earth straylight rejection ,
- pointing stability,
- image dimension stability (focus),
- Detector noise and response stability.

The last one concerns essentially the focal plane architecture and not the telescope itself. The noise is minimised by cooling down the CCDs (-40°C) and the stability is achieved by stabilising the focal plane temperature thanks to inertia. This activity has been managed by LESIA (Laboratoire d'Etude Spatiale et Instrumentation en Astrophysique).

1.2. Straylight constraints

The measurement accuracy shall be better than 10^{-6} that is equivalent to a photon-noise level of tens ph/pix/s in a low earth orbit environment. Thus most of the photons coming from the earth (around 10^{13} ph/pix/s are collected by the entrance of the instrument) shall be rejected before reaching the CCDs level. The baffling requirement is then to reject the unwanted photons with an efficiency around 10^{12}, which is the highest rejection capability ever required for a space telescope of this class.
Such requirement leads to important consequences on the mission and the telescope design (cf table 1):

- Angle between earth and observing sky area shall be limited
- diffusion on optics shall be minimised (low roughness and contamination)
- the most direct straylight rays shall be diffused at least 3 times

Table 1 Requirements imposed by straylight constraints

Parameters	Specifications
Earth position (w.r.t. line of sight)	Between 20° and 90°
Sun position (w.r.t. line of sight)	Between 90° and 270°
Cleanliness (in orbit)	< 2000 ppm
Mirror roughness	< 1 nm
Lenses roughness	< 3 nm
Straylight at CCD level	≈10 ph/pix/s

1.3. Stability constraints

Even if the source is perfectly constant and the detector response is very stable, the spatial response of the pixels is not flat. So a motion of the star PSF (Point Spread Function) on the CCD will affect the exit signal by introducing noise in the measurement. This noise has to be minimised to comply with the mission requirements.

One way to minimise this effect is to defocus the images of the stars in order to cover many pixels for averaging the signal. But in anyway, this technique needs very good pointing stability (at satellite level) and optics stabilities (at telescope level).

An other way is to increase the satellite pointing accuracy by using directly the telescope information. In this method, the instrument is used as a super star tracker and the stars positions, imaging by the instrument, are given in real time (each second) to the satellite AOCS system. This method is implemented on COROT for the first time and should allow to increase the satellite pointing accuracy up to +/- 0.5 arcsec with an active control loop period of 1s.

The following table gives the derived requirements in term of PSF stability.

Table 2 Image stability requirements

Parameters	Specifications
image diameter (defocus around 1 mm)	≈ 240 µm ± 10 µm (≈ 250 pixels)
image diameter stability over 1 orbit (100 min)	< ± 2.7 µm m (± 0.2 pixel)
image diameter stability over 150 days	< ± 27 µm m (± 2 pixel)
Image position stability (over 32 s)	< ± 2.6 µm (± 0.2 pixel)
Telescope LOS drift during life time	< ± 225 µrad (± 20 pixels)

2. TELESCOPE DESIGN

For complying with the above requirements, Alcatel Alenia Space has proposed an optical concept based on an afocal telescope associated with a 2 stages baffle and a camera. This telescope uses very stable materials (Zerodur and CFRP structure) with accurate thermal control loop to guarantee the required orbital stabilities.

2.1. Optical layout

The optical architecture (given in Fig 1) has been essentially driven by the straylight requirements. The advantages of the proposed solution are :

- the presence of a real exit pupil
- the presence a real field stop
- no central obscuration
- the use of simple parabolic mirrors
- the capability to achieve wide field of view
- the low sensitivity to misalignments

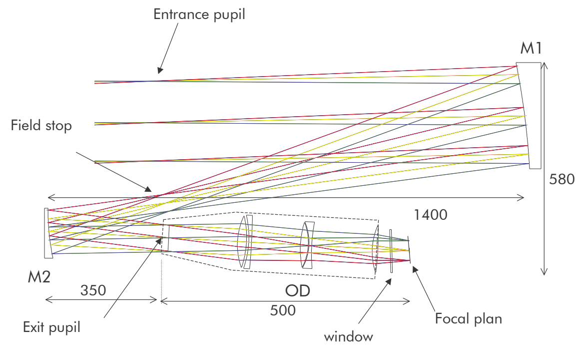


Fig 1 optical layout

2.2. Baffling concept

The baffling concept is driven by the necessity to have at least 3 diffusions for the Earth straylight rays before reaching the focal plane. This imposes to respect the following rules (cf Fig 2) :

- The entrance baffle shall be constituted by 2 stages : one diffusion per stage and the last diffusion on the primary mirror.
- The first stage shall not be seen by the Earth.
- The second stage shall not be seen by the primary mirror.
- The aperture stop shall be placed in the exit pupil plane to avoid its edge illumination (seen by the detector).
- All baffling parts shall be assembled together without any photon leakage.

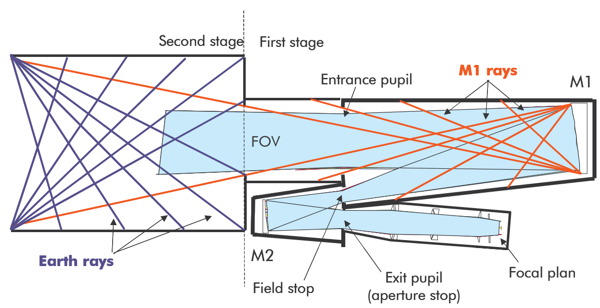


Fig 2 Baffling principle

According to these rules, Alcatel Alenia Space has first designed and proposed a baffling solution based on 3 parts :

- an entrance baffle mainly constituted by the second stage plus the part of the first stage going up to the entrance pupil. The Centre Spatial de Liege (CSL) has verified and confirmed the compliance of this design with the requirements and was finally in charge of the manufacturing and tests of this part.

- a cavity baffle completing the first stage from the entrance pupil to the field stop.
- a M2 baffle closing the optical cavity from the field stop to aperture stop (camera entrance).

The assembling of the baffles were under Alcatel Alenia Space responsibility. A specific joint has been successfully developed for COROT. Its functions are to block photons coming from Earth or sun in a way to allow baffle displacements due to the thermal environment. In the next figure, we can see the mounting of the flexible joints before entrance baffle and camera mounting.

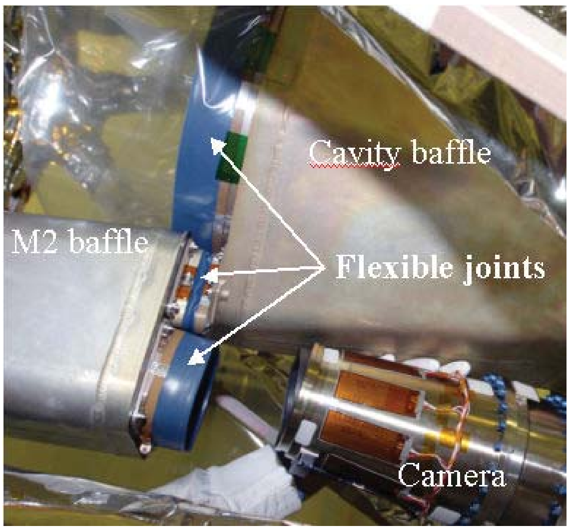


Fig 3 Flexible joints mounting

2.3. Pupil optimisation

The design of the pupil has been optimised with the view to :

- provide the maximum area (for SNR reason)
- minimise the primary mirror size (for cost reason)
- minimise the off-axis degree (for sensitivity to misalignment reason)
- minimise the straylight entries (for performance reason)
- minimise pupil aberrations (for optical reason)

These constraints naturally lead to a non circular shape but a truncated one (cf Fig 4). Moreover, for staylight reason, the aperture stop is placed in the exit pupil plane (to avoid pupil edge illumination). So the stop image at the entrance pupil plane (formed by the afocal system) is aberrant. Thus entrance diaphragm shall be oversized to avoid vignetting but shall also be minimised in dimension to reduce straylight entries. The shape given in figure 4 of the aperture stop, its position and its orientation have been optimised taking into account all these constraints.

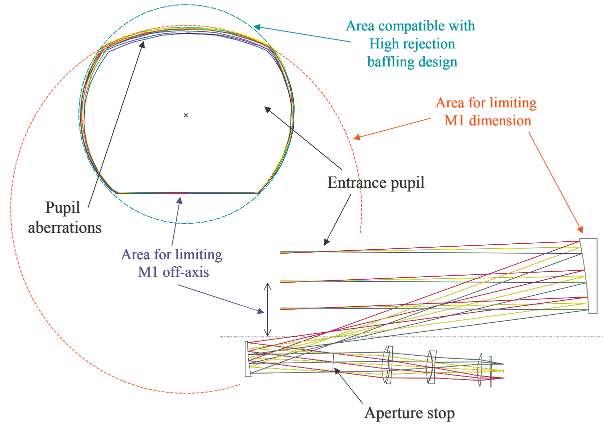


Fig 4 Pupil shape optimisation

2.4. Thermal & mechanical concept

The mechanical design is based on 3 plates associated to 2 trusses structure. For stability reason, the concept is essentially based on carbon fibre (cf Fig 5).

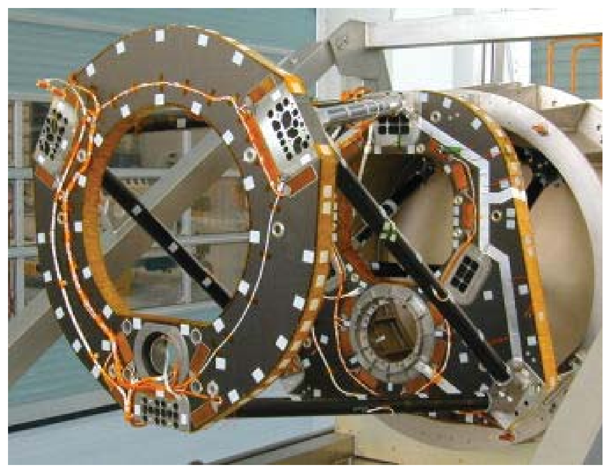


Fig 5 Mechanical and active thermal architecture of the telescope structure

Associated to this very stable structure, an efficient thermal control design has been developed for COROTEL based on active and passive components. Heaters implementation (observable on Fig 5) have been optimised in order to :

- minimise temporal temperature fluctuations
- minimise temporal gradients in structure
- minimise power consumption

Thanks to this optimisation, 5 thermal lines (consuming around 20 W) are sufficient to maintain all the telescope structure in temperature and gradients (during lifetime) within only few degrees. The 2 last

thermal lines, dedicated to COROTEL, are used to control the camera temperature within fluctuations and gradients lower than 1 °C.
Of course, the efficiency of the active thermal control design is closely linked to the passive thermal control design. A first internal set of Multi Layer Insulation (MLI) mattress covers all the stabilized structure parts (fig 6). Then, the whole telescope is wrapped in an external second MLI mattress, in order to avoid External fluxes variations (Sun and Earth fluxes) and to insulate the telescope from the cold deep space environment (fig 7). Adequate material coating and painting complete the passive thermal control in order to minimize thermal gradient.

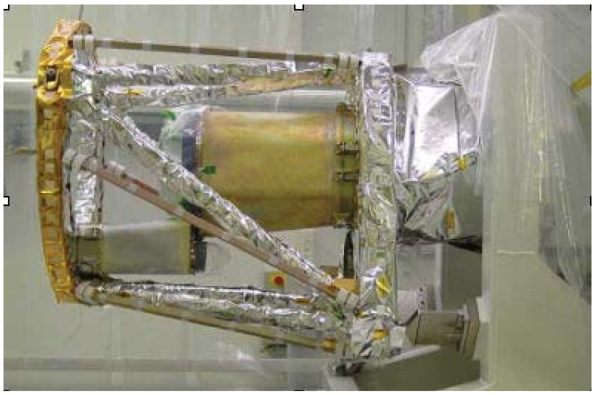


Fig 6 Mounting of internal MLI

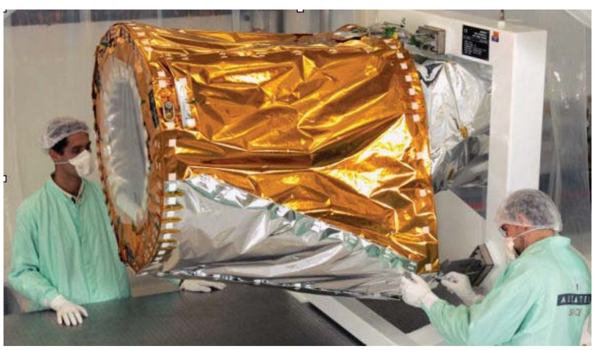


Fig 7 Mounting of external MLI

3. TELESCOPE ALIGNMENT

The alignment and the in flight optical performance of COROTEL were placed under Alcatel Alenia Space responsibility.

3.1. Mirrors assembling

The mirrors (M1 and M2) has been funded by ESA and supplied by CNES with Alcatel Alenia Space specifications. The manufacturer is Sagem-Reosc with direct off-axis realisations. The thermal control of the mirrors has been implemented by Alcatel Alenia Space just before alignment sequence (cf Fig 8).

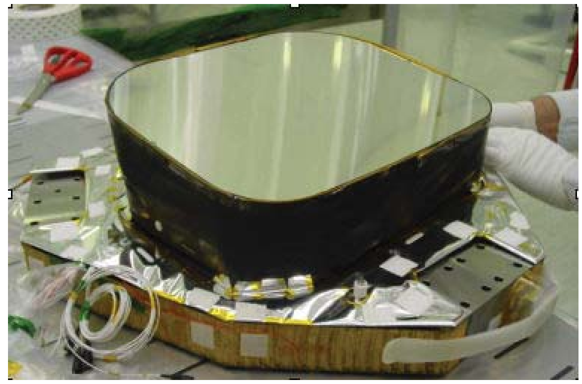


Fig 8 Primary mirror mounted on its plate with black MLIs

The final alignment between M1 and M2 (to realise the afocal telescope) is performed by adjusting the secondary mirror thanks to a precise hexapod device. When the correct position is found (using WFE characterisations), the M2 interface plate is glued on the structure without misalignment by using well mastered techniques in Cannes.

3.2. Camera assembling

The camera (Fig 9) has been manufactured by EADS-Sodern under a CNES contract with Alcatel Alenia Space optical specifications.

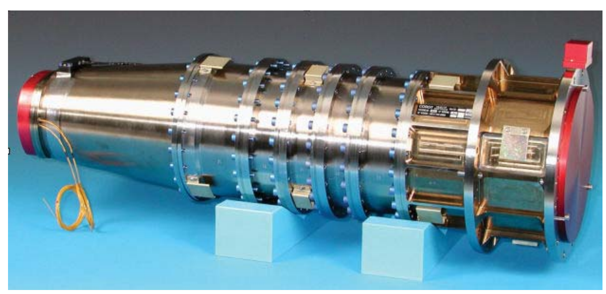


Fig 9 Camera (Sodern view)

The thermal control of the camera has been implemented by Alcatel Alenia Space just before the assembling with the afocal telescope (cf Fig 10).

Thanks to the tolerant afocal telescope concept, the position of the camera is not really an issue. The manufacturing accuracies of the structure and the mirrors interfaces requirements was sufficiently tightened to guarantee a correct final position of the camera regarding the off-axis mirrors. A precise locating at interface level has been also developed to guarantee an accurate reproducibility of the camera mounting.

The final optical quality of the whole telescope has been successfully verified with the presence of the camera before gluing the secondary mirror.

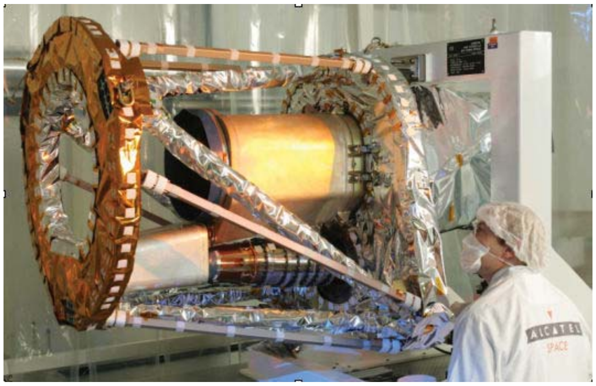


Fig 10 Telescope after alignment

3.3. Optical performance verifications

Once the telescope aligned, the following optical measurements have been performed in air with monochromatic light (632 nm) :

- best focus position : this measure is important at COROTCAM level for adjusting the focal plane in the camera (performed by LESIA). This position has been measured with an absolute accuracy of ± 20 µm in all directions
- focal length
- distortion
- WFE in 13 points in field of view

These measurements were very well correlated with the optical model predictions. Thus the polychromatic characteristics of the telescope in vacuum have been derived by using the optical model. The following table summarised the final optical parameters of the telescope.

Table 3 COROTEL optical characteristics

Characteristics	Measured	Required
Back focal dist.	96.35 mm ± 20 µm	> 90 mm < 120 mm
Focal length	1201 mm ± 2 mm	> 1200 mm < 1210 mm
Distortion	1.6 %	< 5 %
PSF (diam. with 85 % of energy)	40 µm max (prediction)	< 45 µm

4. TELESCOPE VALIDATION

4.1. COROTCAM mounting reproducibility

Before delivering the telescope, it was important to verify that the optical characteristics of COROTEL are maintained after dismounting and remounting the camera. Indeed, the focal plane has to be implemented (by LESIA) on the camera alone. The following figure shows that the WFE before and after the camera remounting remains stable and allows to conclude that this operation does not affect optical quality.

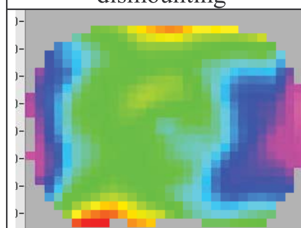
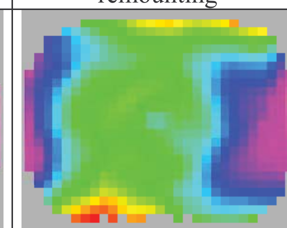
WFE before camera dismounting	WFE after camera remounting
	
84 nm RMS	81 nm RMS

Fig 11 WFE measured at focal plane level before and after the camera remounting.

4.2. Cleanliness control

The primary mirror contamination is a very important parameter from a straylight point of view. The higher is its contamination level, the higher is its diffusion. So the contamination of the telescope has been carefully monitored during all the operations (manufacturing, assembling, alignment, tests …). The following table gives the result of particular and molecular controls.

Table 4 Telescope contamination level measured before delivery.

	Internal baffle		Mirrors	
	particular	molecular	particular	molecular
After manufacturing & assembling	100 ppm	10^{-7} g/cm²	40 ppm	5 10^{-8} g/cm²
After alignment & tests	65 ppm	10^{-8} g/cm²	65 ppm	10^{-8} g/cm²
Total	**165 ppm**	**11 10^{-8} g/cm²**	**105 ppm**	**6 10^{-8} g/cm²**
Specification	*< 220 ppm*	-	*< 220 ppm*	*< 15 10^{-8} g/cm²*

The requirements are met with margin, this demonstrates that cleanliness has been well mastered during all the development.

4.3. Mass control

The mass of the equipped telescope has been measured before delivery and is fully in line with requirements (coming from Proteus).

Table 5 COROTEL mass control

	Measure	accuracy	specification
Structure	92 Kg	± 1.7 Kg	< 96 Kg
Mirrors	8.1 Kg	± 0.2 Kg	< 8.7 Kg
Camera*	31.2 Kg	± 0.5 Kg	< 34 Kg
Baffle*	22.6 Kg	± 0.5 Kg	< 24 Kg
Total	**153.9 Kg**	**± 3 Kg**	**< 162.7 Kg**

(*) the camera and the entrance baffle have been measured and assembled by CNES.

4.4. Qualification status

The aligned afocal telescope has been delivered to LAM on December 2004. For cost and time saving reasons, it has been decided to perform the qualification tests at instrument level (under CNES prime activity). The year 2005 was thus dedicated to the instrument assembling and qualification with Alcatel Alenia Space support for COROTEL. On January 2006, the instrument has been delivered to Alcatel Alenia Space for satellite assembling activities (cf fig 12). Now COROTEL is considered as fully qualified and its thermal model has been up-dated in order to derive performance stability in flight conditions.

Fig 12 Instrument mounted on Proteus platform

4.5. In flight stability performance assessment

As described in the previous chapter 1.3, one of the main requirements for the telescope is its stability short term (1 orbit) and long term (150 days). The following table summarises the foreseen performance of COROTEL in space environments.

Table 6 COROTEL stability performance

Performance	Assessed	Required
Distortion stability	± 0.04 %	< 0.05 %
Image dimension stability (short term)	± 0.18 pixel (± 0.07 %)	<± 0.23 pixel (<± 0.09 %)
Image dimension stability (long term)	± 1.1 pixel (± 0.4 %)	<± 2 pixels (<± 0.8 %)
LOS stability (over 32 s)	± 0.01 pixel (± 0.15 µrad)	<± 0.2 pixel (<± 2 µrad)
LOS stability (over 1 orbit)	± 2.5 pixels (± 28 µrad)	<± 20 pixels (<± 225 µrad)

5. CONCLUSION

Alcatel Alenia Space has proposed a fully compliant telescope design for the very ambitious COROT mission. A very fruitful collaboration between scientists, industries and CNES has allowed to propose elegant solutions associated with a cost saving development approach. The satellite should be launched by a Soyous rocket from Baikonour before the end the year 2006.

AKNOWLEDGMENTS

The development of the COROT telescope has been funded by CNES trough the INSU (LAM-CNRS) COROTEL contract.

For further information about the COROT mission, please note these internet links :

http://smsc.cnes.fr/COROT

http://www.lam.oamp.fr/projets/corot