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The FCI on board MTG : optical design and performances

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THE FCI ON BOARD MTG : OPTICAL DESIGN AND PERFORMANCES

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ABSTRACT - Meteosat Third Generation is the next ESA Program of Earth Observation dedicated to provide Europe with an operational satellite system able to support accurate prediction of meteorological phenomena until the late 2030s. The satellites will be operating from the Geostationary orbit using a 3 axes stabilized platform. The main instrument is called the Flexible Combined Imager (FCI), currently under development by Thales Alenia Space France. It will continue the successful operation of the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on Meteosat Second Generation (MSG) with improved performance.

This instrument will provide full images of the Earth every 10 minutes in 16 spectral channels between 0.44 and 13.3 µm. The ground resolution is ranging from 0.5 km to 2 km. The FCI is composed of a telescope developed by Kayser-Threde, which includes a Scan mirror for the full Earth coverage, and a calibration mechanism with an embedded black body dedicated to accurate in-flight IR radiometric calibration. The image produced by the telescope is split into several spectral groups by a spectral separation assembly (SSA) thanks to dichroïc beamsplitters. The output beams are collimated to ease the instrument integration before reaching the cryostat. Inside, the cold optics (CO-I) focalize the optical beams onto the IR detectors. The cold optics and IR detectors are accurately positioned inside a common cold plate to improve registration between spectral channels. Spectral filters are integrated on top of the detectors in order to achieve the required spectral selection.

This article describes the FCI optical design and performances. We will focus on the image quality needs, the high line-of-sight stability required, the spectral transmittance performance, and the stray-light rejection. The FCI currently under development will exhibit a significant improvement of performances with respect to MSG.

Keywords: MTG, FCI, optical, meteorology

1. MTG FCI MISSION OBJECTIVES

We will first recall briefly the main objectives of the FCI mission.

1.1 Introduction

The MTG program will provide the international community with meteorological and weather forecast data. It consists of two types of satellites : the imager mission named MTG-I, and the sounding mission named MTG-S. The FCI instrument will be mounted on the MTG-I satellites, 4 of them being ordered by ESA, to perform the continuation of service of the MSG mission. The satellites will be operating from a Geostationary orbit above Europe and Africa, using a 3 axes stabilized platform. The FCI is currently under development by Thales Alenia Space, which is the instrument prime, with Kayser-Threde as the main sub-contractor in charge of the telescope development.

1.2 Earth coverage and temporal registration

A major characteristic of the instrument is its flexibility, allowing it to be used in several mission scenario. The nominal scenario is the full disk coverage (FDC), which consists in a full Earth scanning in less than 10 minutes. Alternatively, it is possible to perform only a local area coverage (LAC scenario). For instance, by imaging only the North quarter of the Earth as illustrated in Fig. 1, the duration of the repeat cycle is then proportionally reduced to 2.5 minutes only.
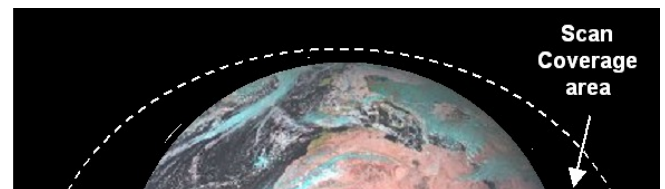

Fig. 1. Illustration of a LAC4 image of the FCI.

The time needed to perform a complete East-West scan swath at the equator is lower than 10 seconds. This means that any two adjacent spatial samples in the image are very well temporally registered, even if they belong to two successive scan swaths.

Finally, any single point on Earth can be acquired by all the 16 spectral channels in less than 0.3 seconds, thanks to a limited in-field separation of the spectral channels. This insures a high level of inter-channel temporal registration, as illustrated in the Fig. 2 below.
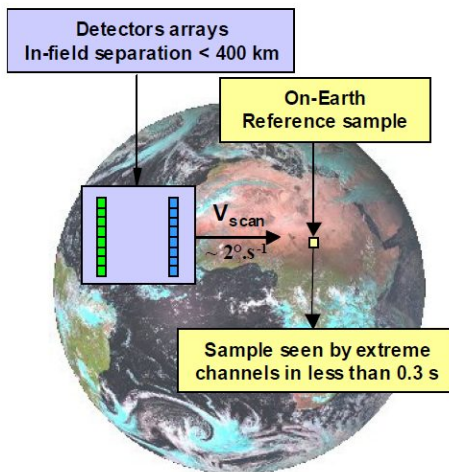

Fig. 2. FCI inter-channel temporal registration

1.3 Spectral sampling

The FCI will produce images of the Earth simultaneously in 16 spectral channels, ranging from the visible spectrum to thermal infra-red, in order to fulfill the scientific needs. The central wavelengths, spectral width (FWHM) as well as corresponding on-ground spatial sampling distances are illustrated in Table 1. The spectral channels are separated in 5 groups named VIS, NIR, IR1, IR2, and IR3. As explained in section 2, the spectral filtering will be achieved in two steps, first thanks to dichroïc beamsplitters in the SSA to separate spectral groups from each other (pure spectral separation, temporally registered), and secondly thanks to spectral filters integrated on top of detector packages (in-field separation, temporal de-registration limited to 0.3s). This architecture was a result of a compromise between inter-channel temporal registration on one side, and limitation of the SSA volume and complexity on the other side.

1.4 On-ground spatial resolution

The on-ground spatial sampling distance (SSD) of the instrument is defined as follows :

- for VIS and NIR channels : 1 km and respectively 0.5 km for high resolution (HR) channels

- for IR1, IR2, IR3 channels: 2 km and respectively 1 km for high resolution (HR) channels

The high resolution channels appear in Table 1 below, when two values are indicated in the spatial sampling distance column. HR channels can also be delivered in low resolution mode, thanks to the binning of adjacent pixel signals performed by post-processing.

In terms of instrument architecture, the spatial sampling distance is the result of the distance between adjacent pixels at detector level, and the focal length of the FCI in each group. The FCI paraxial characteristics are given in section 2.

Table 1. FCI spectral channels definition and corresponding on-ground spatial sampling

Spectral Channel	Central Wavelength, λ_0 (μm)	Spectral Width, $\Delta\lambda_0$ (μm)	On-ground spatial sampling (km)
VIS 0.4	0.444	0.060	1.0
VIS 0.5	0.510	0.040	1.0
VIS 0.6	0.640	0.050	1.0 / 0.5
VIS 0.8	0.865	0.050	1.0
VIS 0.9	0.914	0.020	1.0
NIR 1.3	1.380	0.030	1.0
NIR 1.6	1.610	0.050	1.0
NIR 2.2	2.250	0.050	1.0 / 0.5
IR1 3.8	3.800	0.400	2.0 / 1.0
IR1 6.3	6.300	1.000	2.0
IR1 7.3	7.350	0.500	2.0
IR2 8.7	8.700	0.400	2.0
IR2 9.7	9.660	0.300	2.0
IR3 10.5	10.500	0.700	2.0 / 1.0
IR3 12.3	12.300	0.500	2.0
IR3 13.3	13.300	0.600	2.0

2. FCI OPTICAL DESIGN

2.1 Paraxial characteristics

The following table gives the optical paraxial characteristics of the instrument, as a result of the missions needs.

Table 2. FCI optical paraxial characteristics

	VIS	NIR	IR1	IR2	IR3
Paraxial focal length (mm)	1650	895	450	450	450
Entrance pupil diameter (mm)	300	300	300	300	300
Instantaneous field of view N/S*E/W (°)	0.40*0.40	0.40*0.40	0.40*0.74	0.40*0.74	0.40*0.74

The optical design of the FCI will now be described for each building block, by following the light path which enters the instrument.

2.2 Scanning mirror

The telescope includes a double-gimbaled flat mirror called M0 that scans the full Earth disk. The entrance pupil of the instrument is located on this mirror, in order to minimize its size. At Nadir, the average incident angle of the optical beam on the mirror is equal to 30°. This architecture choice was the result of the need to minimize polarization ratio induced by the reflective coatings at high incidence angles. The following Fig. 3 shows a view of the optical bench assembly with the telescope and the scan mirror. The scan mirror is developed by REOSC.
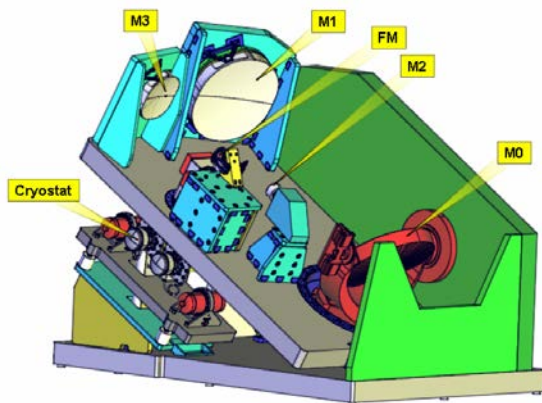

Fig. 3. View of the Optical Bench Assembly with the Scan mirror (M0 in red) and the telescope mirrors

2.3 TMA telescope

After being reflected by the scan mirror, the light reaches a three-mirror anastigmat (TMA) telescope. The characteristics of the mirrors are summarized in Table 3. The end-of-life WFE of the telescope including the scan mirror M0, will be less than 80 nm rms over the whole field-of-view. The telescope has an off-axis angle of 1,4° and the mirror surfaces are aspheric in order to optimize image quality.

Table 3. Telescope mirror optical characteristics

	M1	M2	M3	M4
Radius of curvature (mm)	1361.12	357.40	515.88	Infinity
Conic constant	-0.8763	-6.092	-0.2118	N/A
Optical clear aperture diameter (mm)	335	60	175	68

The mirrors substrate will be Zerodur (except M0 in SiC), which exhibits a very low thermo-elastic deformation. This is needed in order to avoid line of sight drift due to solar illumination. In order to reduce the mass, a light weighting will be applied on the rear face of the mirrors. All the mirrors will have a space qualified silver protected coating, which provides excellent transmission characteristics and good thermal behavior. The fixation on the optical bench will be insured thanks to Invar Mirror Fixation Devices (MFD) glued on the mirror side, as illustrated below. These MFD will allow to filter out the deformation brought by the structure. The equipped mirrors will be developed by THALES-SESO.

Fig. 4. Illustration of the M1 mirror with MFD (THALES-SESO)

The telescope exit pupil is materialized by a physical diaphragm of 40.2 mm diameter, which is the common instrument pupil for all spectral channels. Moreover, an intermediate image is formed after M2 mirror, allowing to insert a field stop. This field stop suppresses any stray-light path outside the field-of-view. After reflection on the mirror M3, a flat folding mirror at 45° named M4, is used to bend the optical beam before reaching the SSA. The Fig. 5 hereafter gives the optical lay-out of the telescope.
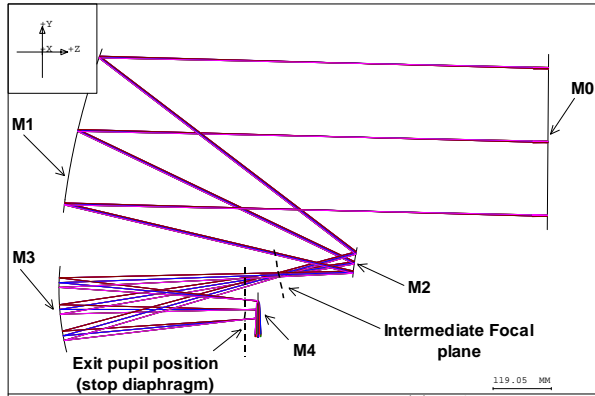

Fig. 5. Optical lay-out of the FCI telescope, as seen from the top

2.4 Baffles

Several types of baffles are implemented in the telescope structure in order to optimize the stray-light rejection :

- a entrance solar baffle, which aperture angle is limited by the need to scan the full Earth to a value about 10°. Its rejection angle is about 20°.
- an inner baffle which protects the entrance cavity from scan mirror M0 to M2, as illustrated in the Fig. 6 below.
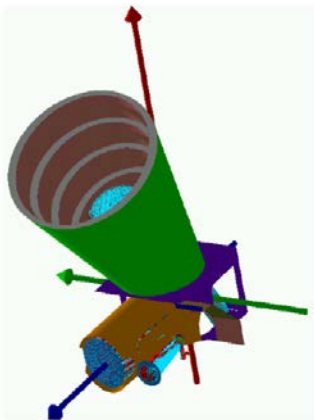

Fig. 6. View of solar baffle (in green, including the vanes) and the telescope inner baffle (brown)

2.5 Calibration mechanism

The FCI being an absolute radiometer, it must be able to perform in-flight radiometric calibration both for solar channels (VIS and NIR) and thermal channels (IR1, IR2, IR3).

- The VIS and NIR calibration is performed by imaging the Sun through a metallic neutral density (MND) inserted in the exit pupil of the instrument. Any spatial inhomogeneity of the density will then be completely averaged out in the focal plane. This component will be made out of fused silica, a material known for being insensitive to radiation, so that its transmittance will remain constant until the instrument end-of-life.

- The IR channel calibration is performed thanks to an embedded flat black-body inserted close to the intermediate image, in order to reduce its size and obtain the best thermal homogeneity. The black body is slightly out of focus to average out any spatial defect.

Both the black-body and MND are carried on a calibration wheel mounted on the optical bench. The mechanism wheel inserts those components in the optical path during calibration mode, as illustrated below. These calibration are performed without interruption the image acquisitions.
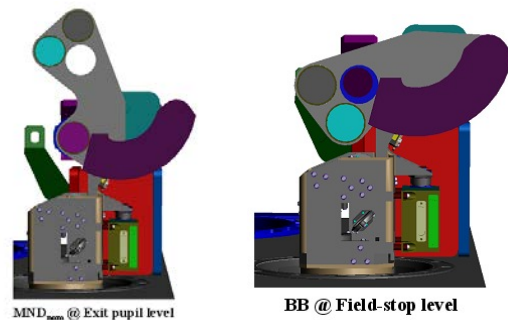

Fig. 7. Illustration of the two calibration configuration of the mechanism (VNIR and IR), and blackbody breadboard

2.6 Spectral Separation Assembly

The Spectral Separation Assembly main function is to separate the optical focused beam coming from the telescope into 5 spectral groups.

- VIS : without changing the focal length of the telescope.
- NIR, IR1, IR2, and IR3 : by collimating the 4 output beams, and adapting the magnification ratio in order to achieve the required instrument focal length for each channel.

For that purpose, the SSA will be composed of the following elements, mounted in a very stable Titanium housing :

- dichroïc beam-splitters, which function is to separate the spectral groups,
- folding mirrors in order to geometrically separate the 4 collimated NIR/IR optical beams at SSA output,
- and lenses in order to collimate the beams. This collimation allows to relax the integration tolerances between the SSA and the cold optics.

The SSA will exhibit an end-of-life WFE in the range of 100 - 200 nm rms depending on the spectral group. The SSA will be mounted on the OBA optical bench, and is illustrated in the following Fig. 8. The SSA is developed by REOSC.
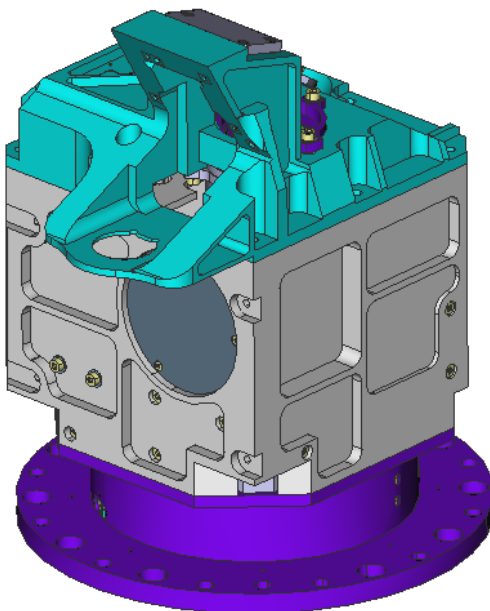

Fig. 8. view of the SSA housing

2.7 Cold Optics

After being spectrally separated and collimated, the NIR/IR optical beams reach the cold optics, which are located inside a common cryostat. When entering the cryostat, the beams first go through an anti-contamination window (ACW) that prevents external molecular contaminants from condensing on cold parts. In order to avoid vignetting, the exit pupil of the SSA is coincident with cold diaphragms on top of the cold optics housings. These cold diaphragms limit the thermal IR background flux received by the detectors. There are 4 cold optics housings, one for each spectral group, which are made out of Titanium alloy. The lenses are in classical IR materials such as mono-crystalline Germanium, fused silica, ZnS and ZnSe. The cold optics will be operating at a temperature about 80K with their full performances. The Cold optics are developed by THALES-SESO.

The integration principle will be quite straight-forward, thanks to tight manufacturing tolerance, and an accurate positioning by pinning both the cold optics and the detectors on the cold plate, in order to ensure a good registration.
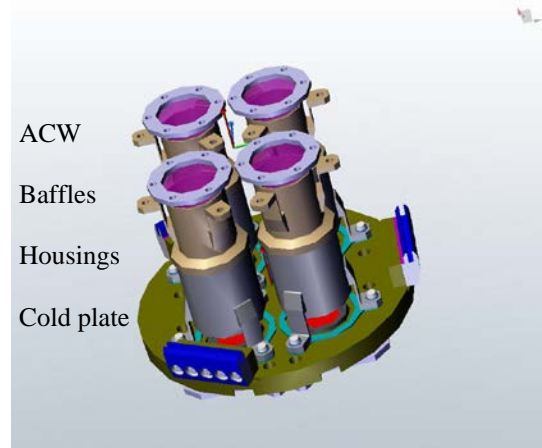

Fig. 9. CO-I housings inside the cryostat, with baffles and anti-contamination windows on top

2.8 Detector Package

Finally, before reaching the detectors, the optical beam goes through spectral filters. There are two kinds of detectors :

- the VIS detector, operating at ambient, is mounted directly on the SSA housing,

- the NIR/IR detectors, operating at 60K for radiometric performances, are mounted inside the common cryostat.

Those filters use the state-of-the art technologies in terms of dielectric coatings. Blocking coatings on the rear face of the filters will allow to achieve the stringent out-of-band rejection requirement of 1%. The NIR/IR filters have been manufactured by REOSC, and the VIS filters by Jena-Optronik.
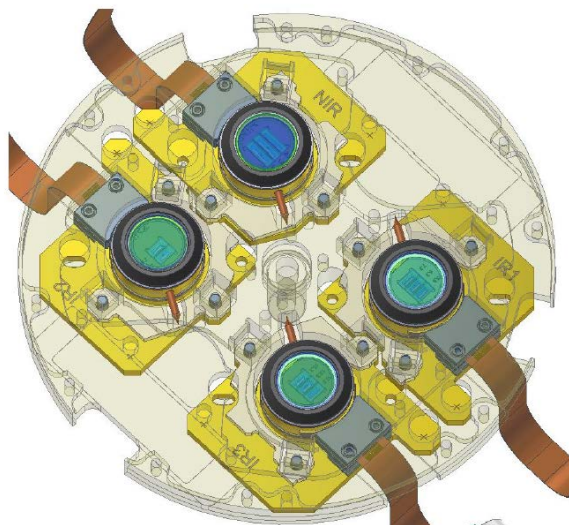

Fig. 10. view of the detectors integrated on the cold plate, with strip spectral filters on top

3. FCI OPTICAL PERFORMANCES

This section presents the main optical performances of the FCI.

3.1 Image quality

One of the main FCI performance is the image quality. It is specified in terms of an MTF template for each spectral channel, for normalized spatial frequencies between 0 and 1 (1 corresponding to the instrument cut-off frequency 1/SSD).

The instrument image quality has been assessed through an exhaustive tolerance analysis on all the optical paths. All kinds of tolerance parameters have been taken into account :

- Manufacturing tolerances
- Integration tolerances
- In-Flight tolerances (hydrostatic stability, thermo-elastic stability, gravity effects, ageing).

To compensate for in-flight tolerances, a one axis refocusing mechanism is located on the M2 mirror, which is the most sensitive one.

The compensators used in the simulation are the following ones, and are representative both of the on-ground alignment process:

- all mirror positions (except scan mirror) for the telescope alignment on-ground,
- detector focus positions thanks to accurate shimming,
- air gaps between lenses inside the SSA and CO-I, during on-ground alignment of these products,

The simulation gives an assessment of the optical MTF, which was then multiplied by the detector MTF in order to compute the overall instrument performance. An example of the computation results is presented in the Fig. 11 below, and shows that the FCI totally fulfills its image quality needs, for all the spectral channels.
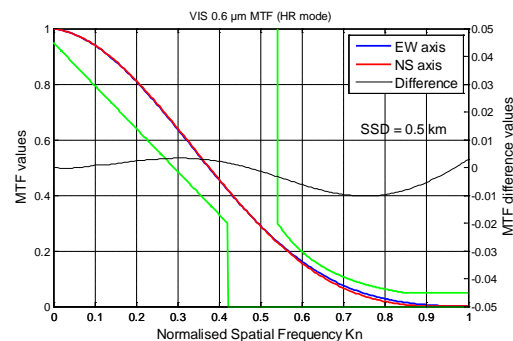

Fig. 11. FCI MTF for VIS 0.6

3.2 Spectral transmittance and polarization

The spectral transmittance is specified through a template for each spectral channel. This function is mainly achieved by the spectral filters. The following Fig. 12 shows the measurement results of FM filters for the NIR 2.2 channel, extrapolated to the operational temperature. A very good fitting to the specified templates is achieved, and the out-of-band rejection is lower than the specified 1% of integrated energy.
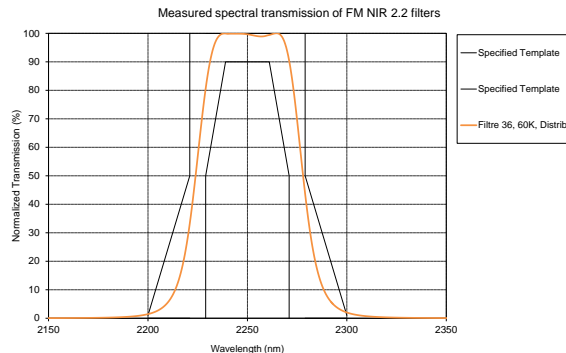

Fig. 12. measured normalized spectral transmittance for NIR 2.2 FM filter compared to the specification

3.3 Line of sight stability

Another key instrument performance is the line of sight stability. Indeed, since the MTG-I will be operating from a Geostationary orbit on a 3-axes stabilized platform, it will be submitted to solar illumination inside the entrance telescope cavity each day around midnight. The other parts of the FCI like the SSA and CO-I are in a very stable thermal environment. Moreover, these thermal conditions will depend on the Sun elevation with respect to the orbit, as illustrated in the following Fig. 13.

In order to minimize the impact of these thermal fluctuations on the telescope line of sight, the most stable materials have been selected. The telescope mirrors substrate is Zerodur and the MFD are in Invar. There is also an active thermal control that regulates the mirror temperature thanks to heaters located on an aluminum plate on the mirror backside, and a radiative mirror insulation thanks to MLI (multi-layer insulation).

The LOS variation of the telescope during a full disk image has then been computed thanks to a thermo-elastic simulation. In the worst case, the LOS stability is better than $\pm$ 2.5µrad around each axis, for $\pm$ 4µrad specified.
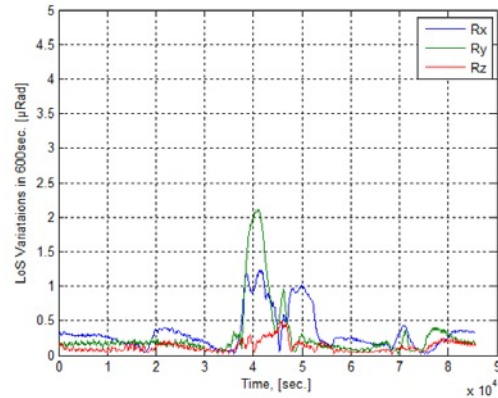

Fig. 13. LOS variation over 10 min during worst day of the year

3.4 Stray-light rejection

There are two different sources of stray-light for the FCI.

- The Sun, which is a punctual source, located out of the instrument field-of-view.
- The Earth, which is an extended source, located inside the field-of-view.

For what concerns Sun generated stray-light, because of the scanning principle the solar baffle aperture angle is limited to the full Earth disk FOV, and not to the instrument instantaneous FOV (refer to Table 2). Consequently, the Sun will enter the entrance cavity around midnight and illuminate the first mirrors. Therefore, the only way to limit scattered stray-light from the Sun is to minimize mirror surface roughness down to the achievable limit of 0.5 nm rms, and to implement a stringent control of particulate contamination. At EOL, the estimated contamination of scan mirror will be lower than 1000 ppm.
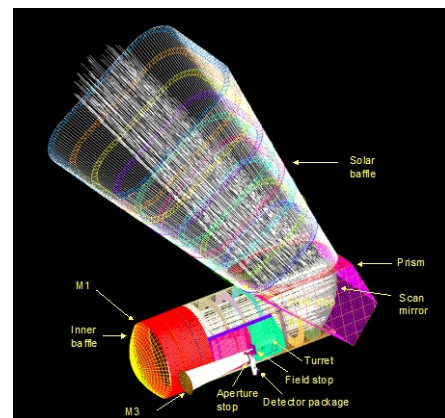

Fig. 14. FCI stray-light model of the VIS channel

Stray-light analyses have been performed at instrument level with ASAP software. Fig. 14 shows a view of the developed model, including optics and baffles. The following Fig. 15 presents the Sun stray-light equivalent radiance level as a function of the angle between the Sun and the line of sight, for the IR3 13.3µm channel.
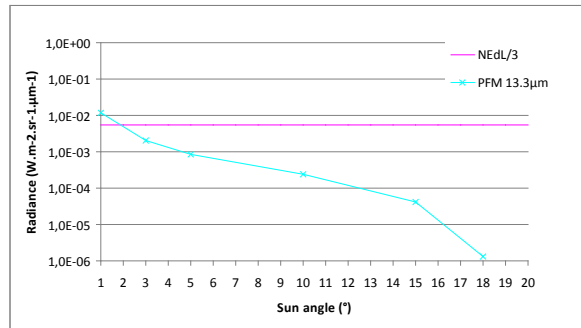

Fig. 15. FCI Sun stray-light simulated radiance for the 13.3µm channel

As shown in the Fig. 15, the Sun stray-light equivalent radiance for the 13.3µm spectral channel, is lower than one third of the noise radiance (NeDL) for solar angles lower than 2°. This shows that the Sun stray-light will not perturb the FCI IR images. Besides, the Sun will only enter the instrument entrance cavity around midnight, when no VIS nor NIR image is taken by the instrument since the Earth is not lighted.

Regarding Earth stray-light, the analyses have shown that the main source of stray-light are the ghost images produced by optical surfaces close to the focal plane. In particular, for the IR channels with a f number of 1.5, the ghost images can be quite spread around the main image. Consequently, the Earth stray-light is controlled by minimizing the optical surface reflectivities, and using black coatings on the mechanical parts. The following Fig. 16 shows the stray-light simulation results for the IR2 spectral channels, when the illumination scene is constituted by a bright half FOV (left portion of the curve) and a half dark FOV. At a distance on-ground higher than 50km from the bright-dark transition (corresponding to 0,6mm at focal plane level in the Fig. 16), the generated stray-light is lower than 0,5% of the irradiance in the bright region.
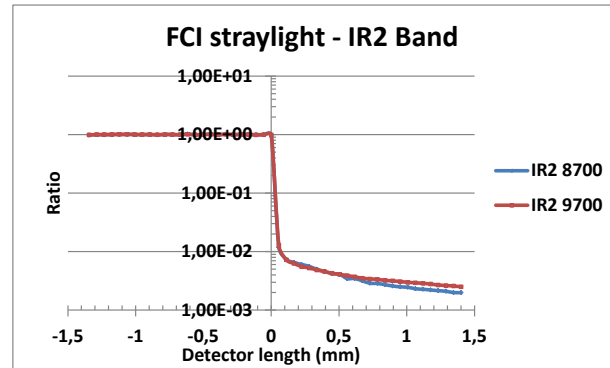

Fig. 16. FCI Earth stray-light simulated radiance for the IR2 channels

4.   CONCLUSION

The Flexible Combined Imager within the Meteosat Third Generation program will pave the way for future weather forecast and climatology needs of the international community. This article first presented the FCI optical design per main units, and then its optical performances in terms of image quality, spectral transmittance, line-of-sight stability and stray-light rejection. The FCI is currently under development by Thales Alenia Space France as prime contractor and with Kayser-Threde as main subcontractor in charge of the telescope. Both imaging and sounding satellites are developed in the frame of an ESA contract. Operating from the Geostationary orbit, this instrument will provide full images of the Earth every 10 minutes in 16 spectral channels between 0.44 and 13.3 µm, with a ground resolution ranging from 0.5 km to 2 km. A compact design, a choice of stable materials to limit thermo-elastic distortion, as well as a modular concept to ease integration, will allow the instrument to reach its outstanding performances.

ACKNOWLEDGMENTS