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TACKLING SUN INTRUSION: A CHALLENGE OF CLOSE COLLABORATION OF THERMAL, MECHANICAL, STRUCTURAL AND OPTICAL ENGINEERS

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I. INTRODUCTION

The Meteosat Third Generation (MTG) program will ensure the continuity and enhancement of meteorological data from geostationary orbit as currently provided by the Meteosat Second Generation (MSG) system. OHB-Munich, as part of the core team consortium of the industrial prime contractor for the space segment Thales Alenia Space (France), is responsible for the Flexible Combined Imager – Telescope Assembly (FCI-TA) as well as the Infrared Sounder (IRS). This paper reports on the analyses of Sun intrusion and the measures taken to reduce the effects of stray light and solar energy input. Optical, thermal, mechanical and structural engineers teamed up to address the extremely challenging performance requirements.

II. SUN INTRUSION, A PROBLEM OF EARTH OBSERVING INSTRUMENTS

Instruments on satellites observing the Earth or the Earth's atmosphere are designed to have a high performance for those illumination scenarios. Any additional power introduced into the system can lead to either degradation of the contrast of the image or thermal/thermo-mechanical instability.

The relative movement of Earth and Sun leads to scenarios in which the Sun is in the vicinity or inside the field of view (FOV) of the instrument. These scenarios occur regularly during normal operation of the system. The criticality of those cases is defined by the time of the duration of such a scenario. For the Meteosat Third Generation Mission a three axis stabilized satellite is used and the two axis scanner mechanism to choose the observed position at the Earths surface is also a new concept. Both leads to possible long lasting static scenarios with sun intrusion into the instruments. Fig. 1 shows the path of the Sun on day 56 of the year as seen by Meteosat Third Generation Infrared Sounder (MTG-IRS). The Sun is passing close to the south pole of the Earth and can illuminate the entrance aperture when the FOV is pointed there.

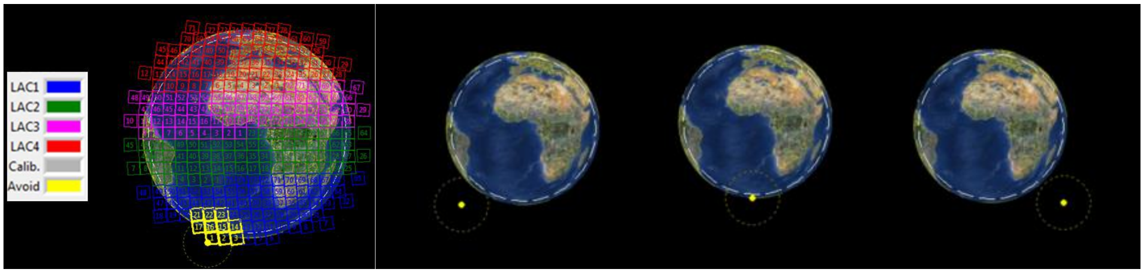

Fig. 1: Scan law and path of Sun on day 56 of the year as seen by MTG-IRS.

Another case to consider is a loss of the satellite positioning. In this case any relative position of the instrument FOV to the Sun is possible, leading to direct Sun intrusion.

In case of solar intrusion within the instrument aperture Sun light can enter the optical cavity even if the Sun is not in the detector FOV.

In particular solar power that is collected by the instrument pupil may enter into the system and due to the nature of e.g. a telescope it may be focused in a small spot with high power density hitting and prejudicing instrument parts. Measures must be taken to prevent performance degradation or even worse permanent damages. Fig. 2 to Fig. 3 show the light propagation in the region of mirror 2, field stop and mirror 4 of the front telescope of MTG-IRS (mirrors in blue). With higher angles of the Sun versus the pointing of the instrument the focused light moves out of the mirror surfaces (and thus will not reach the detector) and hits mechanical parts. At the field stop the focused beam causes high power density on the illuminated parts (Fig. 2).

Even higher angles lead to illumination of mechanical parts close to M1 and M2 causing thermal problems with e.g. MLI shielding or harness of the mirrors. Fig. 3 shows the Sun illumination with 2.8° versus the FOV with a Sun shield in front of M2 to protect the M2 assembly. Also gaps have to be investigated that could cause light entering the cavities behind the mirrors illuminating unshielded mechanical parts.

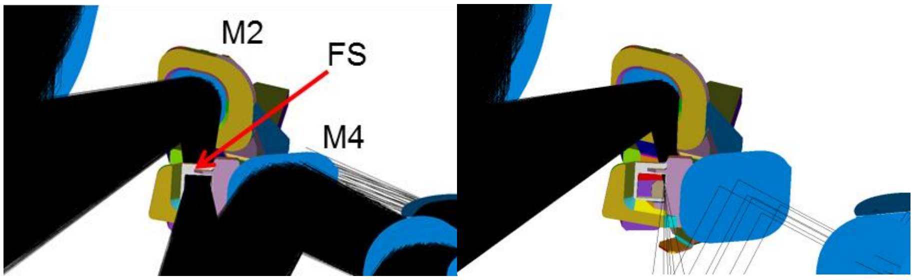

Fig. 2: Nominal path (0.51° half angle) and path of Sun light with 0.8° with respect to the FOV at M2 and field stop of MTG-IRS front telescope optics

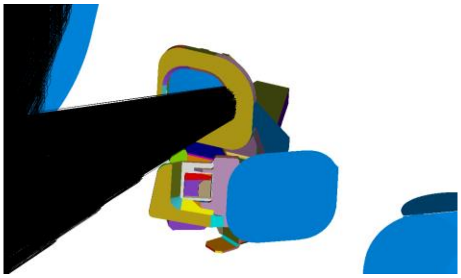

Fig. 3 Path of Sun light with 2.8° with respect to NADIR at M2 and field stop of MTG-IRS front telescope optics.

Fig. 4 shows the Sun spot hitting the MTG IRS front telescope field stop and the resulting power distribution on mechanical parts for Sun illumination at 0.8° with respect to the FOV and the temperature distribution after 180s of Sun illumination within this condition. This temperature profile leads to thermal stresses in the field stop mounting interface (see Fig. 5).

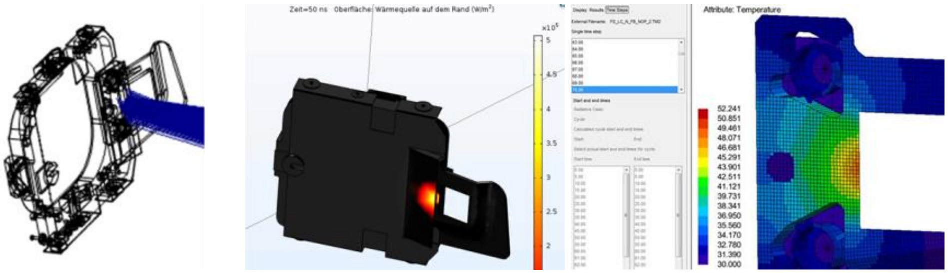

Fig. 4: Illumination of the MTG-IRS field stop by the Sun at an angle of 0.8° to the FOV and resulting temperature distribution

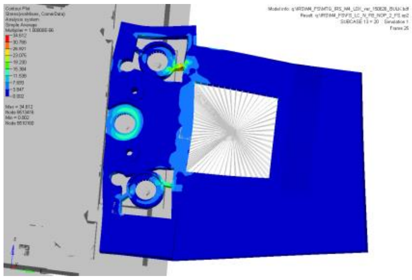

Fig. 5: Thermal stresses due to Sun intrusion on field stop.

Temperatures and deformations have to be analysed and, if needed, the instrument geometry has to be adapted to prevent damage to the instrument due to solar power impact. This design effort has to take into account various different and sometimes contradictory requirements of the participating engineering disciplines.

The Sun propagation within an optical instrument has to be analysed carefully and the design has to consider the related constraints beginning in the early project phase. In particular in large telescope design the issue increases in complexity, main reasons are:

- Large entrance pupil => high solar power into the instrument
- Poor thermal controllability due to e.g. over-heating of mirrors
- Temperature gradient that induces thermo-elastic deformations

Large tolerance chains (mechanical and optical)

- Large dynamic displacements of mechanical structures caused by launch vibrations
- Large alignment ranges
- Complex AIT operation => large clearance required

III. DESIGN PROCESS

In order to reduce the impact of Sun intrusion to the instrument performance a dedicated design process has been developed at OHB-Munich. The design of the instrument has to consider two main aspects:

1. Guarantee that the solar illumination will not degrade the performance of the optics
2. Prevent any permanent degradation of all instrument parts

Point 1) is considered in:

- Selection of materials especially glues and coatings (no degradation of coating due to heating, less power input due to better reflectivity)
- Definition of the operational scenario to minimize sun intrusion times. This includes skipping of earth observation areas when the FOV comes close to the sun (3° avoidance rule)
- The 'Calibration and Obturation Mechanism' Flip Mirror (COM FIM) closes when the Sun would reach the detectors or in case of failure

Point 2) can be performed by a proper design of baffles and local sun shielding (baffling). In fact, the design of the instrument baffling has the double function to protect the instrument thermally from the Sun and to limit the impact of the Sun intrusion on the optical performance. In Fig. 6 the generic baffling design flow is shown.

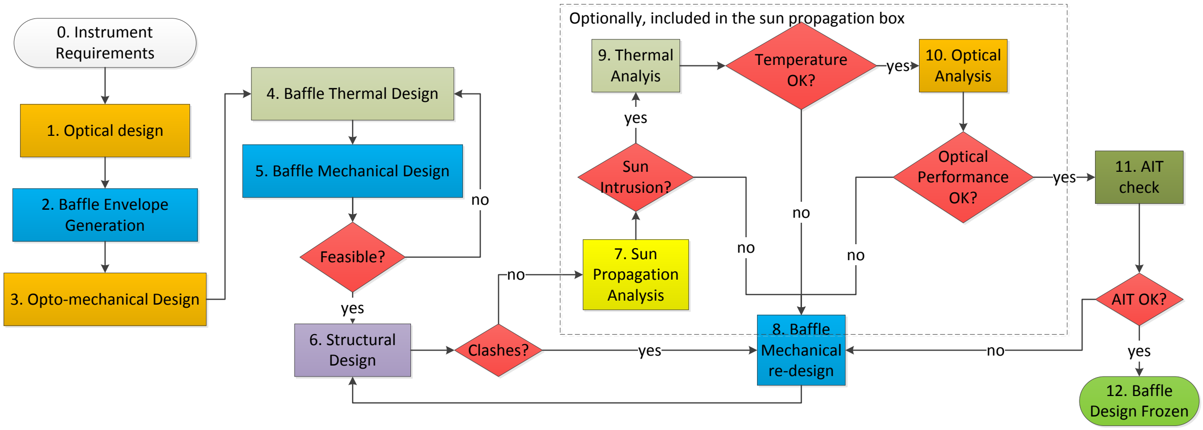

Fig. 6: Design Flow

1. Optical design according to the instrument requirements

2. Baffling envelope generation: The first design step is to define the baffling maximum envelope based on the instrument FOV and other mechanical constraints. The mechanical constraint can be separated into internal instrument layout (e.g. telescope design, MAIT constraints) and external accommodation constraints usually provided as specification (e.g. layout of the satellite, position of the satellite within the launcher).

3. Opto-mechanical design: Based on the defined max baffle dimension (envelope) the optical stray light design can be performed. First the max size of the vanes is defined considering the optical nominal design and the related mechanical tolerances (static and dynamic) and optical tolerances. After consolidation of the vane size their position and number can be established. Additionally, an optical instrument needs to be light-tight (only light propagation within the optical cavity), and for that reason the baffling should be designed as close as possible to the optics to avoid any light penetration on other instrument cavities. A good solution is to oversize the mirror surface to have an overlapping between the vanes and the mirror in the direction of the light propagation.

4. Baffling Thermal design: Once the optical layout of the baffling system has been defined the critical thermal cases are investigated. The thermal analysis results give an indication on baffling mechanical design (e.g. material, coating, thickness). From thermal point of view e.g. thick/massive parts are preferable.

5. Baffling Mechanical design: A first baffling mechanical design is developed trading the optical and thermal constraints together with other design parameters (e.g. cost, manufacturability, mass). Mass is a critical factor and needs to be as low as possible contradicting the requirement of a thick/massive design for thermal reasons.

In this phase it is mandatory to establish a detailed accommodation budget for the baffle design. In particular all the tolerances are investigated and included in the accommodation budget:

- Optical tolerances
- Mechanical tolerances due to manufacturing
- Mechanical tolerances due to integration
- Alignment budget of the mirror
- Dynamic displacement due to:
  - Launch loads (e.g. QSL, sine)
  - In-Orbit loads (e.g. TED - Thermo-Elastic Distortions)

Dynamic displacements contradict the optical need for closed cavities. Mechanical parts need clearance between each other causing gaps that possibly introduce light into the not shielded regions of the instrument.

6. Structural analysis: The baffling mechanical design is verified by structural analysis. In particular a dedicated displacement analysis gives the indication on the minimum clearance needed to avoid any hardware clash between different parts during launch and in-orbit (e.g. between mirrors and baffling).

7. Sun propagation analysis: Once the first baffle design is consolidated the Sun propagation analysis starts. The general flow is shown in Fig. 7.
The first step is to generate a 3D model of the optics and baffling including their surroundings. Usually this operation is performed by importing the CAD of the instrument (or part of it) within the selected analysis tool (e.g. ASAP, COMSOL) including the representative optical design and the correct thermal/optical proprieties of the mirrors and the other elements facing the optical cavity.
To prepare the analysis the satellite pointing constraint shall be considered:

- Nominal operational scenario: when the Sun is in the entrance aperture of the instrument, entrance angles of the Sun light, duration of the Sun intrusion.
- AOCS errors: pointing error during operation, Sun intrusion during fail cases

The two points above determinate with which angles the Sun light enters the instrument.
Finally the analysis has to consider all the deviations from the nominal design, in particular:

- Mechanical tolerances
- Mirror alignment range
- TED

The deviations above can be considered by the definition of a worst case scenario.
The results of the Sun propagation analysis are used as input for a new thermal and, if needed, structural simulation to verify the thermal, optical and mechanical design including AIT aspects. In addition, a updated redesign of the baffle and shielding structures may follow.

These steps usually have to be repeated until a reasonable compromise for the contradicting restraints of optical, thermal and structural needs can be found. Fig. 8 shows the baffle and shielding components introduced in the MTG-IRS front telescope to reduce Sun intrusion and stray light impact on the instrument.

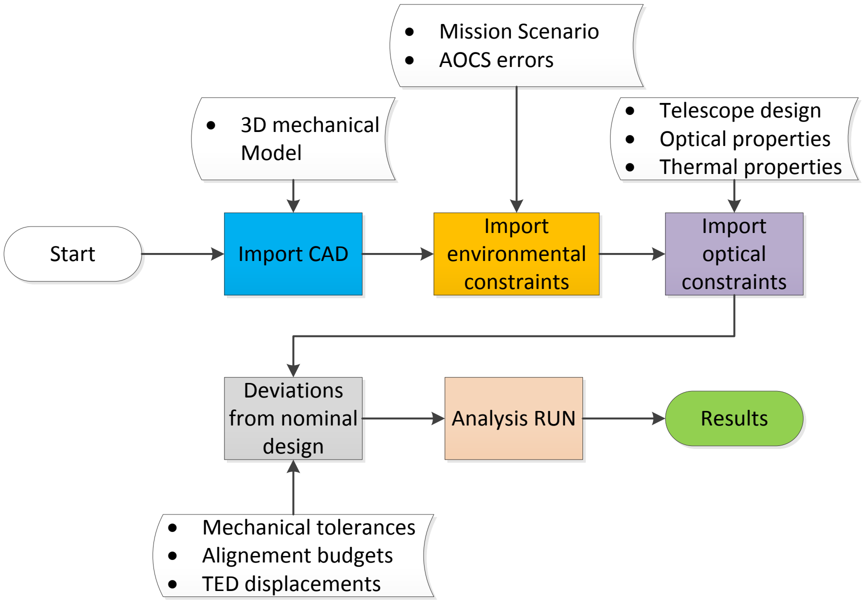

Fig. 7: Sun propagation analysis flow

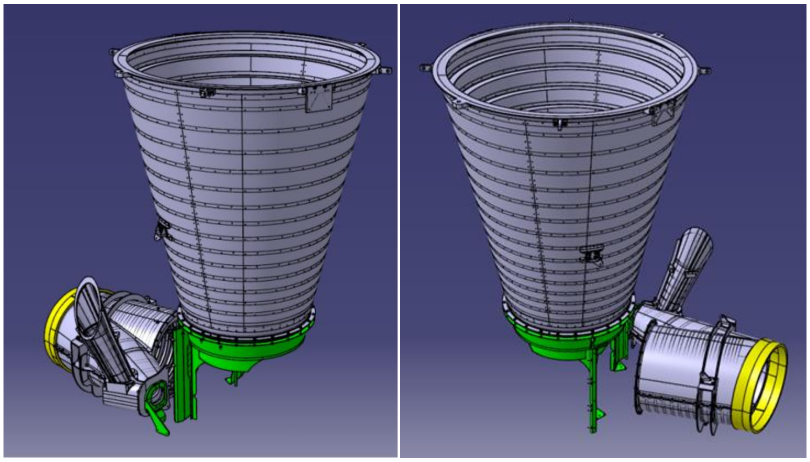

Fig. 8: Baffle and shielding components introduced for Sun intrusion and stray light reduction

When preliminary design assumptions, budgets and requirements are violated during the project development (e.g. large displacements, large alignment range, high temperatures) the complete design loop has to be repeated to generate a non-conflicting design baseline. Design modifications have to be implemented and checked in all models to secure the instrument design and performances.

An example of FCI-TA vane thermal analysis is shown in Fig. 9 and Fig. 10.

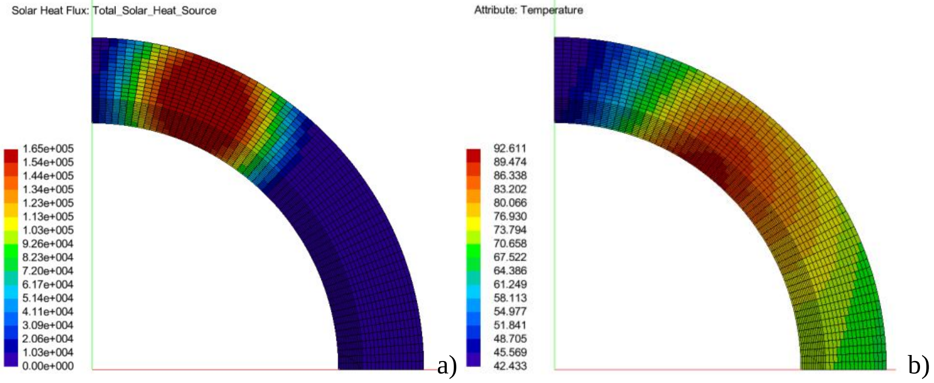

Fig. 9 Thermal analysis on the baffling vanes; geometrical model of a vane with Sun spot

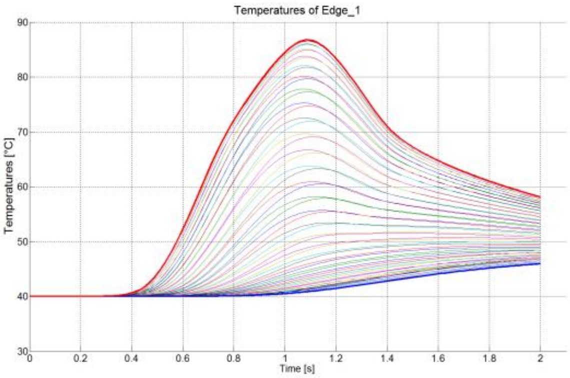

Fig. 10: Thermal analysis on the baffling vanes; example of temperature profiles

In the example different designs of the baffling vanes have been traded to identify the best compromise in term of thermal stability vs. mechanical design. Different cases of solar intrusion have been considered. At the end a proper mechanical design has been selected in term of material, geometry, mass, coating, manufacturing process, etc.

IV. MULTIDISCIPLINARY DATA EXCHANGE

For the analysis loop dedicated tools for the different purposes are applied.

1. The optical system and all beam information is built within ZEMAX.
2. Mechanical parts are created in CATIA V5, applying the optical system and the beam information as constraints/limitation.
3. The CAD geometry is simplified and imported into ASAP. Optical surfaces are imported from ZEMAX. Optical properties are applied to all relevant surfaces and sources according to the possible Sun positions. The result of the simulation are the ray paths through the system and the deposited power on the different surfaces. Power distributions can also be generated in an arbitrary ASAP format.
4. The CAD geometry is imported and simplified in ESATAN-TMS. A mesh is created and optical surface and material properties are applied to it. In addition boundary conditions (e.g. orbit simulations, sink temperatures etc.) are defined. The power distribution simulated in ASAP will be imported into the thermal model to be used as power input to simulate the temperature distribution.
5. The CAD geometry is imported into NASTRAN. A mesh is created and boundary conditions are applied. The temperature distribution has to be imported into the structural model to simulate thermal stresses and dilation.

The performance of this chain of simulations interfacing different tools is crucial and time consuming. No direct transfer of results is possible due to different input and output formats of the tools.

Interfaces in this simulation chain are:

(1) CAD – ASAP; CAD – ESATAN, CAD – NASTRAN

For all simulation tools the complete geometry has to be imported. To do so the CAD model has to be reduced and simplified or de-featured to allow smaller systems in the simulation tools and spare simulation time. Each tool has different internal descriptions and needs a different degree of simplification and de-featuring of the geometry. Hence, this translation has to be repeated in every tool.

(2) ZEMAX – ASAP and optical surfaces to CAD geometry

The imported CAD surfaces of the optical elements lack in quality for the optical simulation. Tessellated surfaces show different beam behavior than smooth optical surfaces. Therefore the imported surfaces have to be defined as optical surfaces in ASAP. The imported ZEMAX geometry includes the correct optical parameters but for mounting and light weighting the outline of optical elements often is not elliptical or rectangular but has complicated outlines. The optical surface has to be adapted to these outlines to generate closed volumes for the optical elements. Otherwise rays could enter or leave e.g. a lens without interacting with the lens surface.

(3) ASAP – ESATAN

Result of the ASAP simulation is the power distribution on the optical and mechanical elements. Rays are traced from the source until they are fully absorbed in the system. It is possible to create power distributions on plane surfaces or in volumes. These distributions are equidistant and always defined in the local coordinate system. ESATAN needs to have the geometry meshed to be able to calculate heat fluxes in the thermal nodes. The mesh normally is not equidistant and parallel to the coordinate axes so that the values from ASAP cannot be directly connected to the nodes of the mesh. The easiest way to include the ASAP results into ESATAN is to create a new source in ESATAN with the power and the spot-size of the ASAP results. But this is only possible with reasonable effort when the power distribution or the spot is homogenous. Otherwise the power distribution has to be mapped to the ESATAN mesh manually. This has to be done for every Sun position simulated.

(4) ESATAN - NASTRAN

Both tools use a meshed geometry but the meshes and the grade of simplification of the geometrical models is different. Where the thermal simulation shows a high degree of de-featuring i.e. no holes, chamfers and edges, the structural simulation geometry consists of mixed meshes (solids (3-D) and shells (2-D)) and shows a high level of details (Fig. 11). OHB-Munich has developed a tool to map the thermal results to the structural simulation geometry [1] (MultiPass, a thermal mapping tool). Fig. 12 shows the flow of the mapping process.

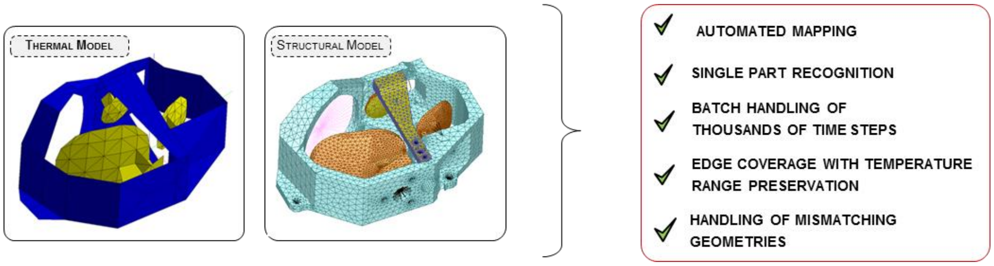

Fig. 11: Thermal mapping tool parameters

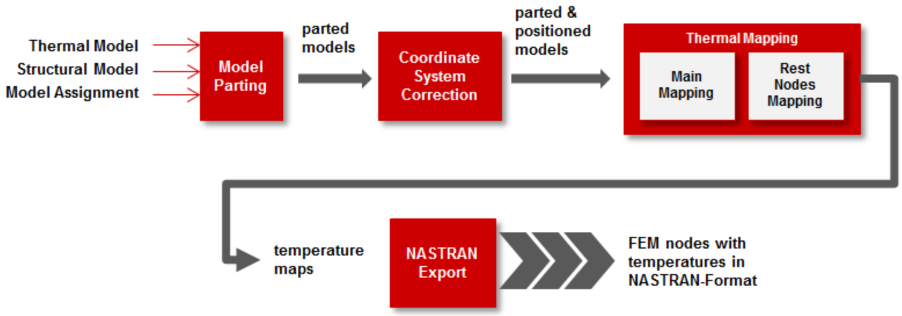

Fig. 12: Mapping process flow

With this tool the geometry is first divided into single parts. The model parting must detect/prescribe the part limits. The meshes are also read in. Thermal mapping is done in two steps: First the algorithm defines temperatures for the main structural (FEM) nodes as a function of thermal elements. Then the not covered structural areas are defined based on available temperatures by interpolation (no further use of the thermal model). This creates the temperature maps for the structural simulation and is exported in a NASTRAN format.

All parts and the temperature mapping have to be verified visually. The thermal mapping tool allows a faster conversion of thermal simulation data to structural temperature input. The mapping has to be done for every Sun position and, in case of time dependent simulations, for every time step.

V. SUN INTRUSION VERIFICATION

Sun intrusion verification shall be done in a space simulator. An exemplary facility (LSS in ESTEC) can be described as follows: Three parts comprise the thermal vacuum chamber: the main vacuum chamber, where the instrument is placed during the test, the auxiliary chamber, where the mirror and the cryo pumps are located, and the seismic block, installed at the bottom of the main Chamber with the aim to accommodate the interface structure to the instrument. Between the instrument and the seismic block a spin box or other structure to rotate and shift the instrument is installed.

The Sun simulator consists of lamps whose radiation is projected through an optical integrator onto the collimation mirror placed in the auxiliary chamber. Its purpose is to provide a homogeneous parallel light beam with respect to the horizontal plane and the rotation around the vertical axis of the main chamber.

In principle every Sun position can be simulated within these facilities since the instrument can be rotated and tilted with respect to the incoming light. The problem arising here is that these facilities are built for thermal test of the full instrument structure and not to reproduce the beam inside the optical instrument. The divergence of the simulated Sun beam is larger than the divergence of the real Sun (most space simulators have a minimum cone angle around 2°) leading to larger spots inside the instrument during test compared to space. Depending on the position inside the instrument and the type of Sun simulator the spot size can be up to seven times larger inside the IRS instrument than the real solar spot in flight reducing the power density by a factor of 49.

Sun intrusion verification with the existing space simulators is fully representative up to M1 where the light is not focussed. At M2 the spot has roughly double the size (Fig. 13) but (for Sun in the FOV) is still fully on the mirror so thermal simulations could be simulated for the reduced power input and compared to the test.

At the field stop the spot size is multiple times as large as the nominal Sun spot (Fig. 13 b). Here the test conditions are too far from the real in-orbit Sun intrusion conditions to predict thermal effects.

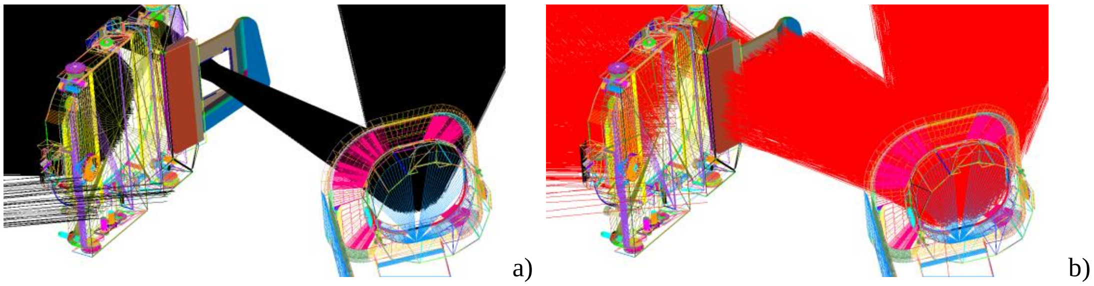
a)
b)

Fig. 13: Spot size enlargement at M2 and field stop of MTG-IRS for Sun divergence angle 0.25° (space) (a), and 1.9° (test facility) (b) solar cone angle.

To correlate the used models to the Sun intrusion test in a space simulator the models have to be adapted to the larger source. ASAP simulations have to be performed to predict the spot size and power distribution inside the instrument. The ASAP power distribution then has to be mapped to the ESATAN mesh for a simulation of the larger solar source. Thermal predictions can then be established with the adapted model considering the sun simulator behavior which can then be used to assess the test results.

VI. CONCLUSION AND WAY FORWARD

The solar intrusion in large optical instruments for Earth observation is are an important issue to be understood and considered during instrument design because it may lead to instrument performance degradation or even to permanent corruption of the instrument functions.

The mitigation of the Sun intrusion impact on a large optical instrument is a multidisciplinary task where all the technical disciplines are involved. In the frame of the MTG project OHB-Munich has experienced the definition and implementation of a design process to properly identify and analyse the effects of Sun intrusion. The analysis results have been used to implement mitigation options to secure the instrument design.

Due to the multidisciplinary nature of the topic, the design loops within the design flow are time and cost intensive. For that reason OHB-Munich is currently investigating a methodology to improve the efficiency of the design loop reducing duration and cost. At the same time OHB-Munich is targeting the generation of a process which may even produce more accurate and reliable analysis results.

The first step is to reduce the inefficiency of the model exchange. Interfacing between simulation tools is inefficient and error prone. Values have to be inter- and extrapolated to match the meshes of other simulation software. For the interface between ESATAN and NASTRAN a special mapping tool has been developed by OHB-Munich. This tool reduces the time needed for mapping by about a factor of 6. Two options are available for the exchange between optical and thermal simulations:

- Extend the mapping tool for mapping of ASAP results to ESATAN meshes.
- Use of a single tool for all three simulation tasks, and thus, removing the necessity of model exchange.

With applying an extended mapping tool the advantages of single simulations would be preserved but the overall development time would not reduce sufficiently. On the other hand ASAP, ESATAN and NASTRAN are ESA approved simulation tools.

The use of a single tool will reduce the need of importing the CAD geometry into different programs, and changes in geometry will only have to be implemented once. Results of one simulation will be directly used for the next step of the design flow.

OHB-Munich has kicked-off an investigation to consolidate the needs and potential improvements of the analysis chain. This investigation includes also a tool survey

VII. ACKNOWLEDGEMENTS

In the frame of MTG development, OHB-Munich as the IRS Prime has run analyses on the IRS instrument and the FCI-Telescope assembly to investigate Sun intrusion in those instruments. Results of this paper are partially based on this work that was funded by ESA through MTG satellites development program.

The authors acknowledge that this work is supported by an ESA funding through the MTG satellites development.

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