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Structural and Thermal Analysis of EMIR

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ABSTRACT

This paper shows the different design concepts and techniques employed in the structural and thermal analysis of EMIR (Espectrógrafo Multiobjeto Infrarrojo), nowadays under development at the Instituto de Astrofísica de Canarias.

Keywords: Spectroscopy, Image movement, Structural Analysis, FEA, Cryogenic.

1. INTRODUCTION

The EMIR mechanical design is driven by the stringent top level requirements of use in it the Nasmyth foci, by the presence of large optical components, and by the image stability requirement for a rotation of the instrument of 180° better than 55 μm in imaging mode and 5.5 μm in spectroscopic mode along the spectral direction (37 μm in spatial direction). The concept of the EMIR structure has been developed to fulfil the constraints imposed by the optical layout and the accessibility criteria, to minimize flexures (increasing its stiffness) and to meet the GTC interface requirements. The most relevant structural performances are described, including the image movements obtained from the CODE V optical model using the Finite Element Analysis (FEA) data as input.

2. EMIR STRUCTURE DESCRIPTION

A general description of the EMIR Mechanical layout can be found in [1]. The Cryostat is supported from the GTC Nasmyth Rotator (NR) flange by the Nasmyth Rotator Adapter (NRA). This attachment causes the whole instrument to rotate together with the NR. At the other end, a Nasmyth Platform Adapter (NPA) helps holding the instrument , providing additional stiffness to minimise the effects of flexure and providing an alignment mechanism in order to facilitate the assembly of the instrument in the telescope and to achieve an appropriate load distribution between the rotator and the platform. The NRA is connected to the instrument's Support Plate (SP), which is the structural mainframe of the Cryostat. Up to this point, all the components mentioned belong to the "warm" part of the instrument, that is, these components remain at room temperature and pressure. The structural main frame of the Cold Structure of the instrument is the Optical Bench (OB) which holds and pre-cools the optical and mechanical subsystems of EMIR. The OB is supported and thermally isolated from the warm SP by means of three Axial Support Trusses (AST) and six Radial Support Trusses (RST). Figure 1 shows each component of the EMIR structure.

3. OPTICAL BENCH DESIGN

The EMIR OB concept is based on a H shaped cold bench formed. The central flat plate, with a preliminary thickness of 65 mm, is the main member where all optical components are supported and it provides stiffness in one direction. Two perpendicular flat plates (lateral plates or "wings"), with a preliminary thickness of 50 mm, provide stiffness in the other direction. The circular plate, with a preliminary thickness of 70 mm, located at the centre of gravity of the cold structure (OB plus all subsystems mounted on it), constitutes the support area in which support trusses (radial and axial ones) are linked with the SP. The interface area of the structure with the first barrel of the collimator has a thickness of 40 mm in order to allow the optical alignment.

The OB is a structure which both material and manufacture process is being studied nowadays. The material baseline is Aluminium alloys 6061-T6 or 6082-T6 but depending on the final decision about fabrication it could be changed. From the point of view of manufacturing two options are being considered: casting or machining. In the case of machining, the attachment between substructures is being studied too with three options: welding, mechanical assembly with bolts or mixed solution (welded-bolted structure).

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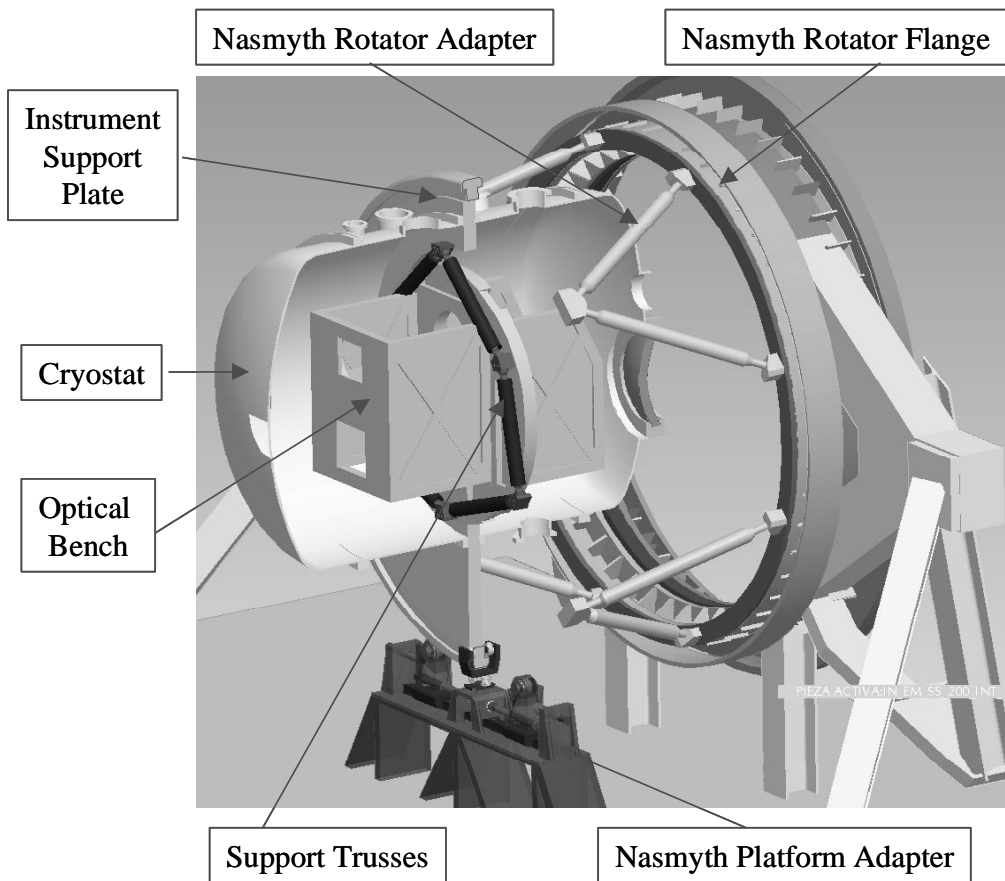


Figure 1. EMIR Structure

OB short term evolution includes re-positioning of subsystems interfaces and mass optimisation. In order to facilitate accessibility during subsystems mounting-demounting operations, interfaces of them with the OB shall be located on the top plane of the lateral plates (“wings”) except for the case of the Detector Translation Unit, which interface remains in the central plate to assure the displacements coupling with the camera. Mass optimisation of the OB shall be done according to two main criteria: maintain the image movement in the detector within the values of previous models and maintain the rigidity of the structure in those points or zones where this shall be necessary. Mass optimisation process shall be done and evaluated by means of FEA models and image movement process. Figure 2 shows two different views of the EMIR OB.

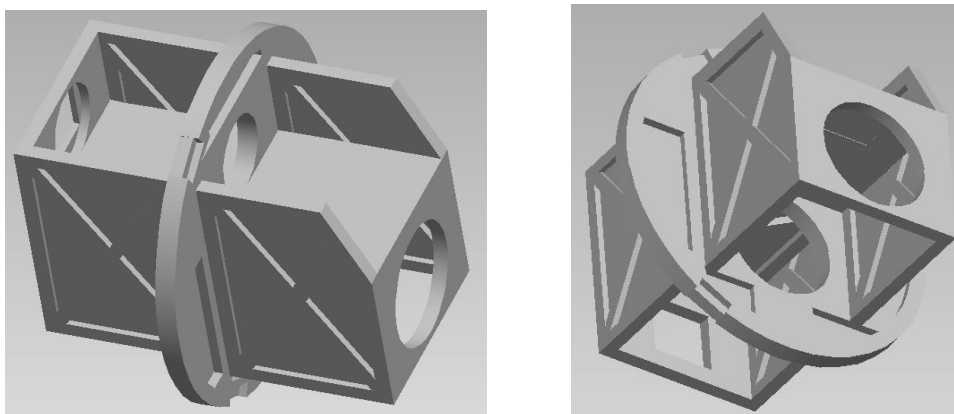


Figure 2. EMIR Optical Bench.

4. SUPPORT TRUSSES DESIGN

4.1 Concept

The EMIR OB is supported by means of a Radial Support Trusses (RST) and an Axial Support Trusses (ATS). It consists of two separate structures that withstand the forces which acts in radial and axial directions. RST consists of an arrangement of trusses which are loaded in plane through the apex. AST are simple bars directly loaded in tension or compression.

The concept of the RST is applicable if the ends of the trusses are articulated. In practice the use of bushings or end rods in cryogenic applications is not feasible; also, the stiffness of this mechanisms is, often, insufficient. The alternative solution proposed for EMIR is to reduce the bending stiffness of the trusses at their ends: the stiff section of a truss transforms in a solid section with the axial stiffness, but a much lower moment of inertia and bending stiffness. The bending of this *flexure* end provides the stress relief that allows the trusses to accommodate temperature deformations whilst maintaining a high rigidity in its own plane.

Due to the limitations in the amount of heat conducted through the trusses and the foregone high stresses appearing in the thinnest section of the flexures, the G10 epoxy composite and the Stainless Steel A-310 will be considered as manufacturing materials for the trusses and flexures respectively. Figure 3 shows the RST mounted on the OB.

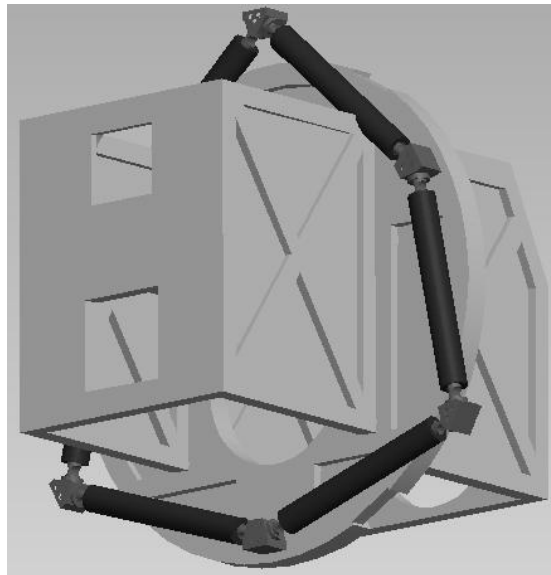


Figure 3. Radial Support Trusses mounted on the OB.

4.2 Flexure characterization

One can find in the literature diverse empiric equations to characterize the rigidity of different flexure types [4,5]. These equations are based on laboratory experiments and finite elements developments. For EMIR, a specific rod flexure characterization was developed in order to guarantee the behaviour of the radial trusses. Therefore a parametric study was done using the programming language of the commercial program Ansys, that characterizes the rigidity of the flexure due to axial and flexural loads. The parameters of the study are the diameter of the cylinder D and the radius of the notch r . See Figure 4.

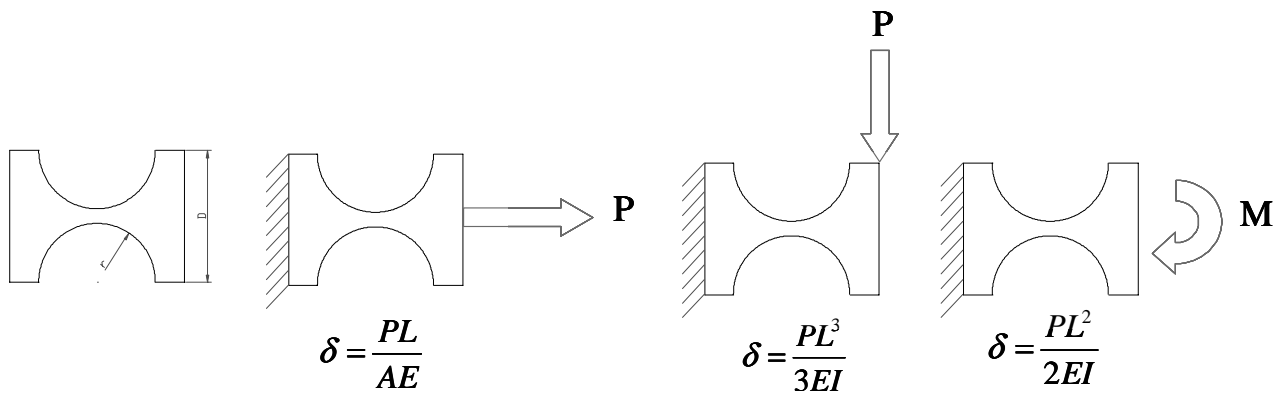


Figure 4. Parameter and load cases for the flexure characterization study.

This study provides empirical equations that allow to know the axial and flexural stiffness of the flexure for any reasonable combination of notch radius and diameter.

Figure 5 shows a typical mesh with the restrictions, symmetry conditions and joints to assure the uniform application of the load. Figure 5 also shows two examples of results in displacements due to traction and flexion.

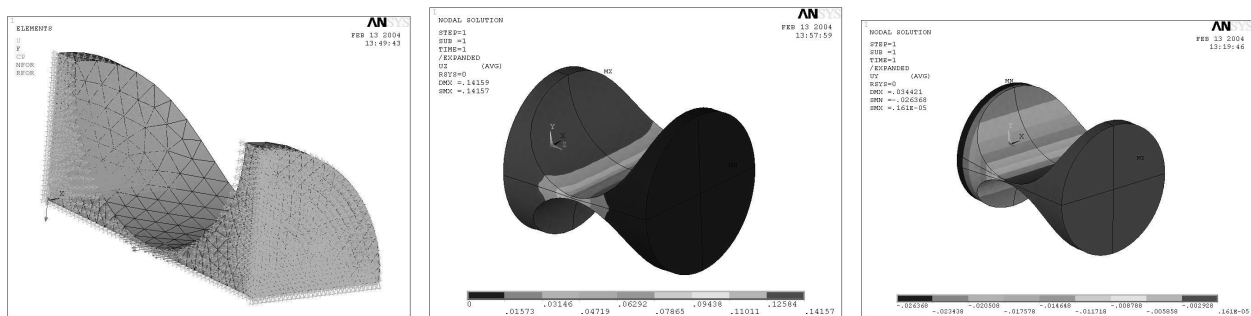


Figure 5. Typical mesh of the study (left) and load results due to traction (centre) and flexion (right)

4.3 Flexure Detailed Design

The flexure should fulfil the following requirements:

Axial stiffness: The preliminary calculations have been carried out considering an articulate bar. Adding two flexures in the ends with the objective of simulating the articulations will cause a change in the axial stiffness of the bar. The flexure should have enough axial stiffness so that it does not commit the rigidity to traction of the bar.

Flexion stiffness: The rigidity to flexion should be minimized in such a way that the flexure completes its function as articulation. It is necessary that the flexion stiffness is several orders of magnitude smaller than the bar stiffness.

Stresses: The flexure should absorb the thermal contraction of the central disk of the OB without reaching the elastic limit.

Once selected the flexure to be used, one can proceed to the verification of the complete support, analysing the solicitation due to thermal contraction and the weight of the OB.

Figure 6 shows the four-node tetrahedral mesh used for both analyses. Notice the mesh density used in the area of the flexures. The flat plate simulates the dimensions of the central disk of the OB.

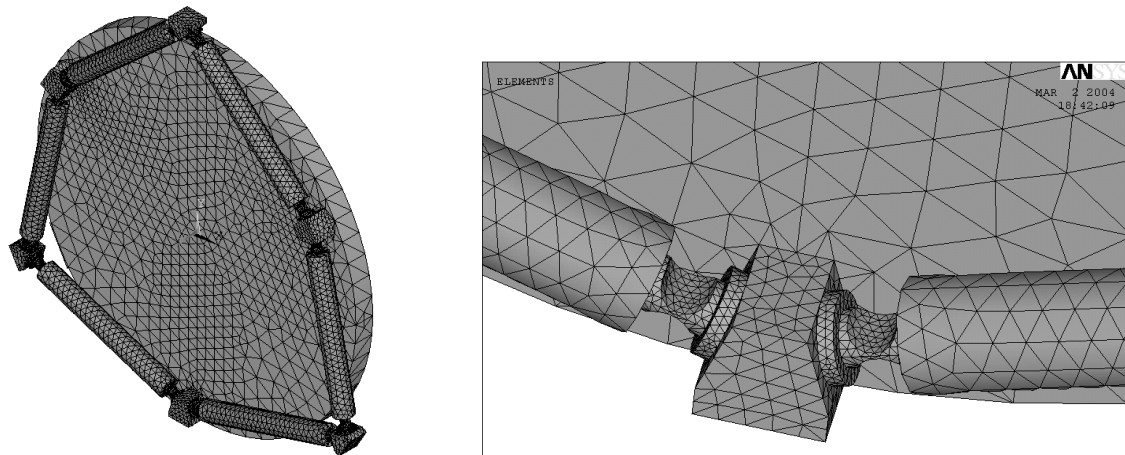


Figure 6. Finite element mesh use for thermal and elastic analysis

4.3.1 Thermal contraction

The calculation of thermal contractions is carried out as a problem of coupled fields, calculating the distribution of temperatures along the RST (Figure 7) assuming an uniform temperature of 77K in the plate and 293K in the external blocks of the RST. Once calculated the distribution of temperatures, these are translated as body loads to the structural module, in which the displacements of the external blocks of the RST are restricted.

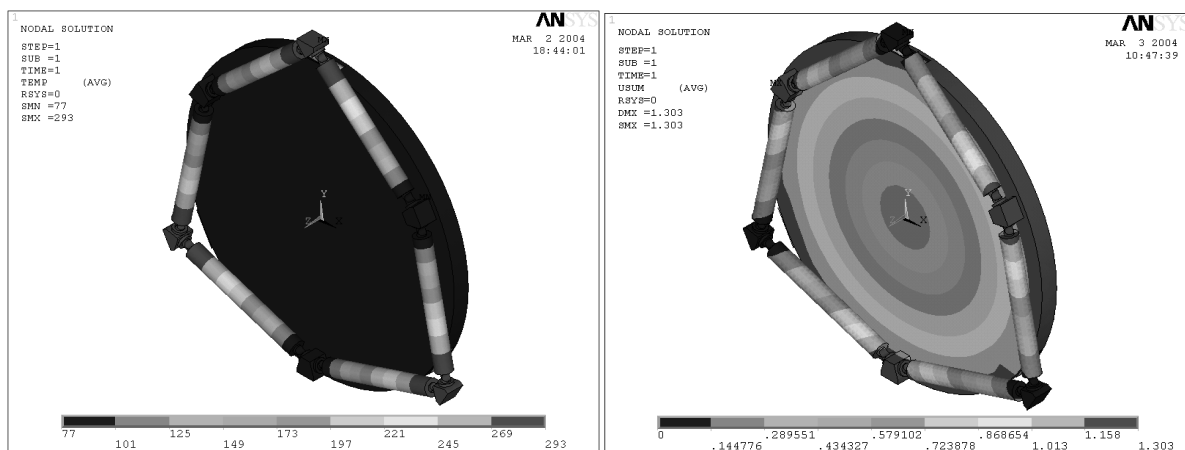


Figure 7. Temperature distribution (left). Thermal contractions of the support (right)

Due to the thermal contraction and the forces produced during the cool down, the centre of the plate moves 1.5 μm in the X and Y direction, indicating the correct athermalization of the RST, since the high stresses shown in Figure 8, are only concentrated on the flexures, just as it was expected.

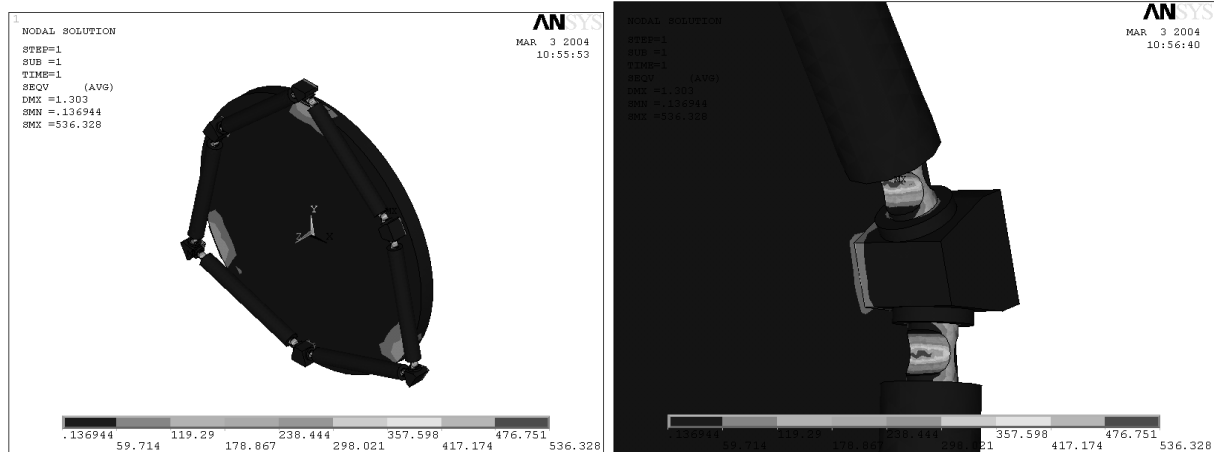


Figure 8. Steady state Von Mises stresses

4.3.2 Gravitational loads

Figure 9 shows the total displacements of the central plate when a load of 12000N, corresponding to the weight of the OB and the whole cold subsystems, is applied at the centre of the plate.

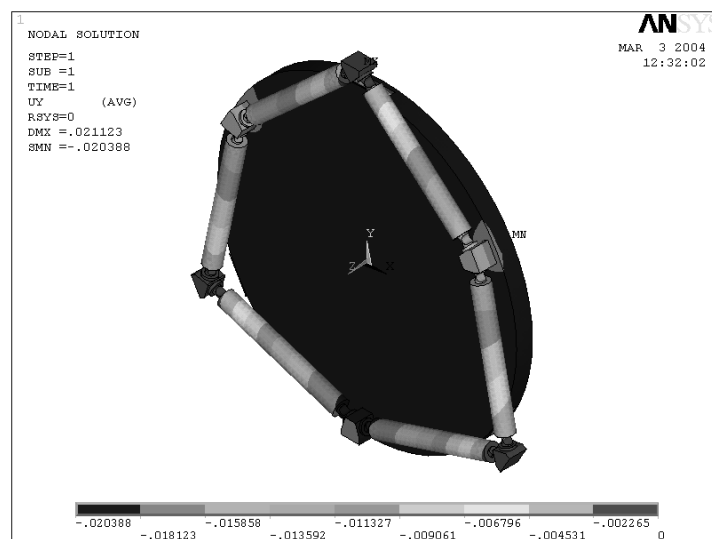


Figure 9. Displacements of the central disk due to the weight of the optic bench, optical components and mechanisms.

As it is observed in Figure 9, the maximum displacement of the structure due to the weight of the whole cold mass is 20 μ m.

The joints between the end of the flexures and the SP are done by means of screws just as it is observed in the Figure 10. An epoxy will be used to glue the AISI A-310 with the G10. The characteristics of the epoxy and the gluing process will be defined by experimentation, manufacturing a prototype of the RST and AST in scale 1:2. This prototype will be cooled down in the EMIR Multipurpose Cryogenic Test System (EMCTS) [1] during 2004. Figure 10 shows the detailed design of this prototype, mounted in the EMCTS.

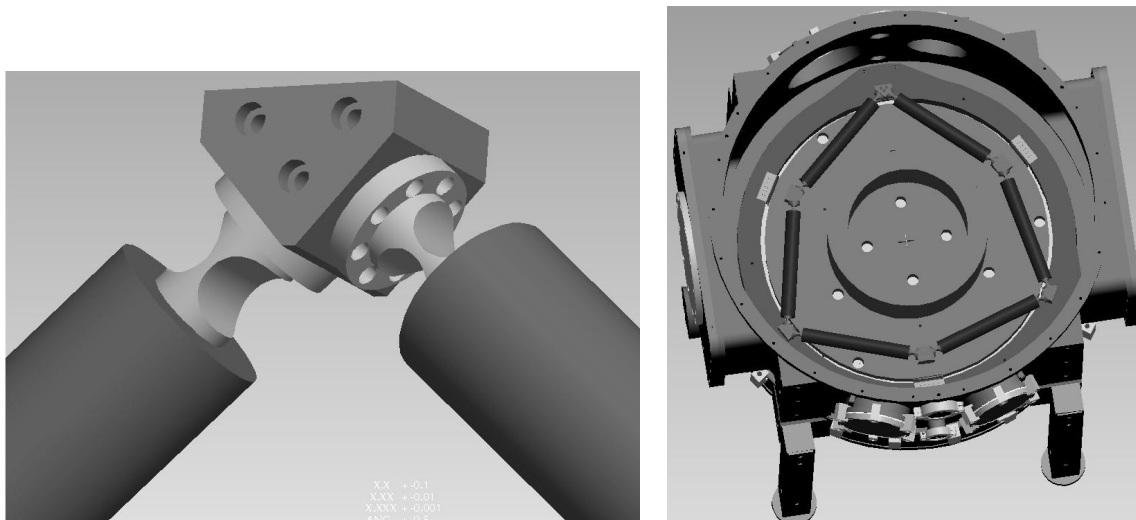


Figure 10. Joint details and image of the Support Trusses prototype mounted in the EMCTS

5. IMAGE MOVEMENT CALCULATION

5.1 Errors sources

The image stability budgets are contributed by three main terms:

1. Passive gravitational flexures of the instrument structure, assuming all subsystems are rigidly attached to their mechanical interface with the OB.
2. Passive module flexures of each optical subsystem with respect to the interface with the OB.
3. Flexure compensator mechanism errors

Term #1 is allocated (in spectroscopy mode) to the relative displacements and tilts of the involved optical elements with respect to the slit, due to gravitational deformations of the cold structure. The spectroscopic budget is not affected by the displacement and tilt of the whole instrument with respect to the telescope rotator.

Allocation of term #1 in image mode is to the absolute displacements and tilts of the involved optical elements with respect to the telescope (the NR flange, where the interface between EMIR and GTC is situated), due to gravitational and thermal deformations of the support structure and the cold structure.

Term #2 is allocated to the relative displacements and tilts of the involved optical elements with respect to their interface with the OB.

Term #3 is allocated to the residual errors of the compensation mechanism.

Image displacements due to terms #1 and #2 arise from two different sources:

1. Repetitive and predictive errors due to elastic flexures of the EMIR main structure and substructures. Errors can be modeled and corrected by the compensator.
2. Non-repetitive errors, including: thermal and structural hysteresis, mechanisms backlash and non-compensated residuals from the repetitive contributions. These errors cannot be compensated and are the values allocated in the corresponding Error Budget (EB).

5.2 Flexure compensation

The detector movement along local axis X_D and Y_D is used for compensation of slit image and spectrum displacements on the detector due to gravitational flexures of EMIR cold structure and involved optical modules.

Movement is performed by a flexure-based mechanisms [1] having the capability of lateral displacements of the detector on a given range. Image stabilization is performed actively on an open-loop mode, extrapolating the detector X and Y positions from the calibrated values obtained from a look-up table for a given position respect to the g vector.

The compensation is made on the central field, having a residual movement of the field edge due to non-linear optical effects. Terms that produces a zero displacement on the center (like rotations) are not compensated.

5.3 Error allocation procedure

Figure 11 shows a schematic breakdown of the instrumental flexure into its mayor components. The division between structure flexure and module flexure is a practical one, based on the way flexure can be modeled with FEA.

5.3.1 Uncorrected field errors

It includes image movement errors allocated to terms #1 (structure) and #2 (modules) after compensation

5.3.2 Elastic Components

Because of the large FOV of the EMIR camera, the motion on the central field due to flexures is not the same as the one at the edge of the field. This is a second-order effect compared to the general image translation. However, because the detector translation cannot correct those differential movements inside the field, it imposes a limit to the mechanical flexures in EMIR.

Image displacement residuals allocated to gravitational flexures of the instrument structure after compensation are predicted from a combined FEA/Optical Analysis. The input is a realistic structural configuration of EMIR, obtained from the structural sensitivity analysis, the optimization criteria and general structural design considerations. The error sources are the displacements and tilts of each contributing component for the load cases associated to the different positions of the gravity vector. All these contributions are coupled and their values are obtained using a FEA model of the structure for each position of g vector. These data are transferred to the optical analysis program as displacements and tilts of each component. FEA was made using ANSYS 8.0, and the optical analysis was made using CodeV 9.20

The output from the optical model is the variation of the requirement as a function of the rotator angle and the telescope elevation.

Image displacements allocated to module flexures after compensation are predicted from the results of the FEA of substructures and the sensitivity analysis

5.3.3 Hysteresis and Backlash

Image error allocated to hysteresis is a 10% of the non-compensated displacements for solid or welded structures (like the OB)

Image error allocated to elements attached to mechanisms having structural hysteresis, movable elements (like bearings) and mechanical play is a 30% of the non-compensated displacement. This is the case of the grisms

5.3.4 Compensator errors

Image motion due to detector translation errors is allocated to the absolute accuracy of the translation mechanism (due to actuator resolution and calibration errors), the incremental accuracy of the mechanism (and control drive), its overall repeatability and the measurement error of the instrument position

5.4 Finite element model

Modelling and manufacturing are fundamental points related to the structure design. Correct modelling is important because optical performance of the design is analysed through model results. Moreover, one design can be disregarded on this basis. On comparing results, models must be equivalent. The word equivalent, however, is difficult to define in this context and involves many modelling details.

Manufacturing is important because both feasibility and the associated costs. But on designing the structure of an optical instrument both go together. We must design so that the manufacturing process will not introduce important factors that cannot be covered by the modelling. Truss elements are really convenient from the weight optimisation standpoint but perfect hinges do not exist and then, a truss model is not realistic in a displacement model. Beams models are more realistic, but beams joint stiffness depends on the number of beams meeting at the joint and the kind of beam. A thin walled beam can present flexibility near the joint that cannot be accurately modelled by simple beam theory. If we will model with beams, joints must be designed so that beam theory hypothesis is fulfilled.

Another important fact, sometimes disregarded, is that finite element models converge, if the formulation allows it, to the mathematical model of the physical structure. Then, we need to be sure that our mathematical representation, i.e.: solid, plates, shells or beams, is correct within the structure.

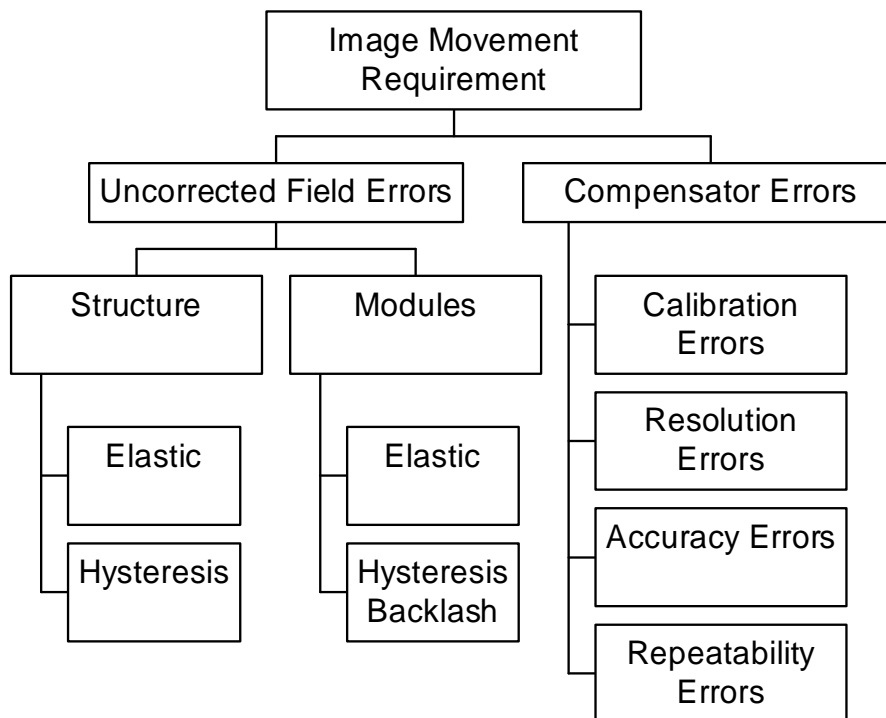


Figure 11. Flow chart showing the structure of the image movement error budgets

In our experience, flat or mild twisted plates, can be adequately modelled by plate elements with shear corrected displacements. Near joint flexibility can be accounted with a fine mesh. This is not the case for a beam. To use small beam elements will never account for the beam wall flexibility.

The OB structure is simulated with 8 node shell elements. The support trusses and support structure are simulated with 3D beam elements with convenient shear correction factors. The masses of the optical components are simulated with structural mass element.

Each substructure mass is located at its centre of gravity and attached to the structure interface points with a low stiffness beam element, to not increase the local stiffness of the structure. The load transmitted is correct but the mass displacement is meaningless. For all the subsystems no detail more than its weight and structure attachment points are considered.

Figure 12 shows a representative finite element of the EMIR OB and RST. Notice the joint between the subsystems masses and the structure. Also OB displacements due to the gravity vector acting in vertical (X) direction are shown.

5.5 Result post processing

The results of the finite element program were processed in order to produce useful data for the optical analysis.

The optical components behaviour is reduced to that of a plane triangle attached to three points at the interface plane. The displacements and rotations are calculated as follows:

Displacements U_x , U_y and U_z of the three points are averaged. These three points form a triangle which centre is located –approximately, due to discretization errors- at the interface centre.

Normal vectors to the undistorted and to the distorted triangle were calculated. These vectors are normalized and its vector product gives us the tip and tilt of the triangle. In order to compute the rotation of the plane around its normal, an in-plane vector joining the triangle centre of gravity and one of the nodes is defined and normalized. The vector product between its undistorted and distorted positions is taken as the third rotation.

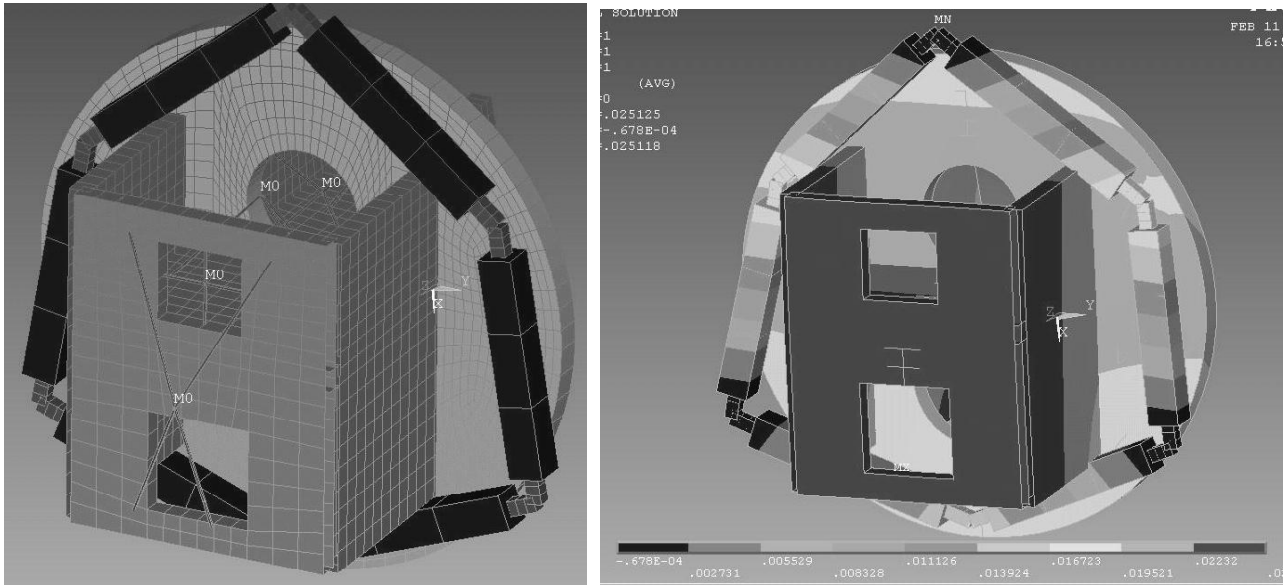


Figure 12. Finite element mesh and gravitational displacement of the EMIR OB and RST.

5.6 Flexure analysis

The displacements and tilts of the more contributing optical components (camera and detector) -relatives to each local coordinate system and with the instrument turning about the Z axis are shown in Figure 13 to Figure 14.

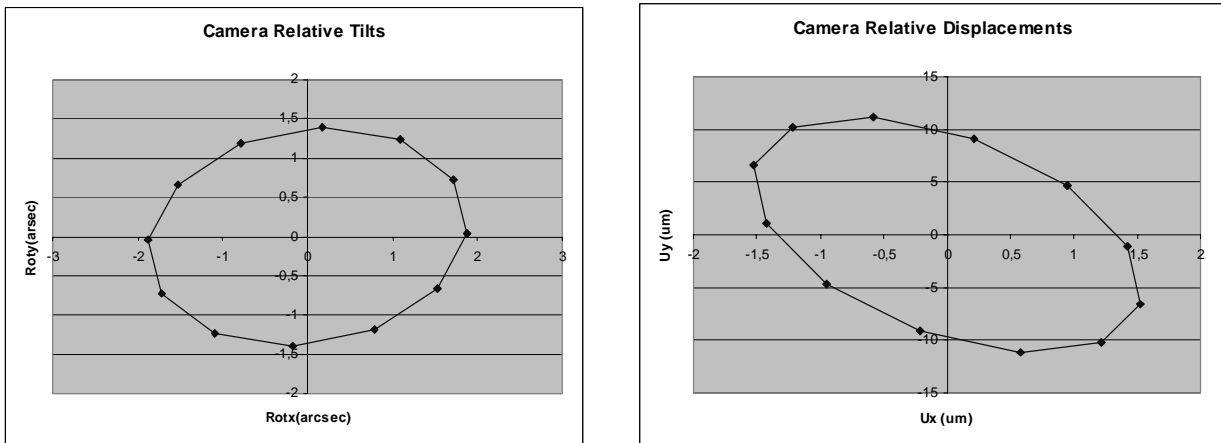


Figure 13. Camera relative displacements and tilts

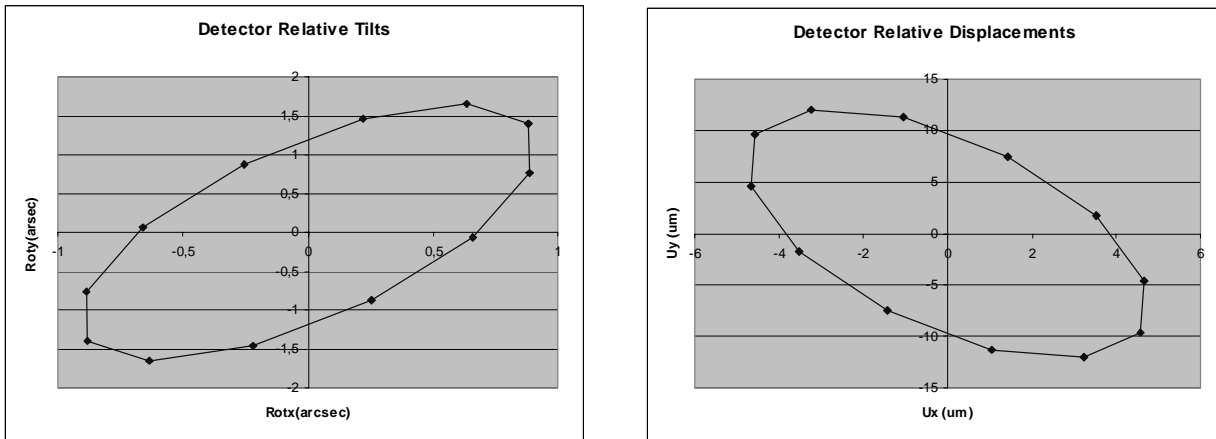


Figure 14. Detector Relative displacements and tilts

5.7 Structure elastic contribution to the Error Budget.

Figure 15 shows the X and Y displacements (X spatial direction, in horizontal. Y spectral direction, in vertical) of the image on the detector in spectroscopic mode, due to gravitational flexures of the cold structure, on non-compensated and compensated upper slit. Each dot on the figures corresponds to an angular position of the telescope rotator. Non-compensated image displacements are larger in the spectral direction, showing a certain anisotropy in the structure or in the loads distribution on it. Compensation performs very well on the centre field. Image movement roughly decreases from $\pm 6 \mu\text{m}$ in spectral direction axis without compensation to $\pm 0.25 \mu\text{m}$ within the most unfavourable case with compensation. Compensator gain factor is 20 or better.

Image movement allocated to elastic deformations of the EMIR cold structure within the compensated EB is $2.5 \mu\text{m}$ ($\pm 1.25 \mu\text{m}$), a security factor of 5 above the value predicted by the FEM Image movement allocated to elastic deformations of the EMIR cold structure within the non-compensated EB is $30 \mu\text{m}$ ($\pm 15 \mu\text{m}$), a security factor of 2.5 above the value predicted by the FEM

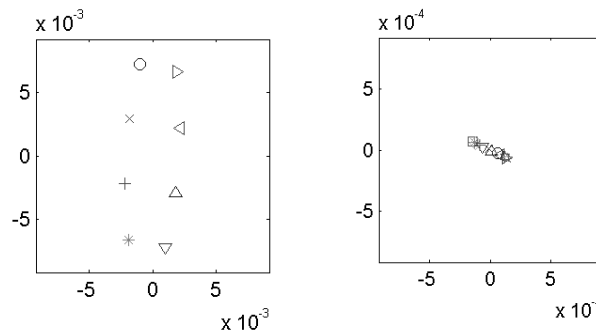


Figure 15. Upper slit non-compensated(left) and compensated (right) IMSM.

6. SUPPORT STRUCTURE DESIGN

The NRA is a bar structure of four triangles/side where all the structural components work in traction or compression, with no turns at centre. The main member of each bar is a tube and the ends are rods that work as flexures. This is essential in order to avoid the turns of the whole structure with respect to the fixed end, at the same time, it makes manufacturing easier. The central flange shall be located at the gravity centre of the instrument. The NPA, shown in Figure 16, is located at the central flange in order to share the total weight of EMIR with the NRA, at the same time that the turns of the instrument are minimized due to the flexions. This support shall permit the alignment in the XY plane of the instrument (the Z axis is the optical beam axis). The Y alignment is provided by means of a fine pitch screw that

moves the two rolling bearings in opposite sense, displacing the central flange vertically. The X alignment is provided by means of a lateral screw that displace the whole system horizontally. A central bearing with a preload system is provided in order to assure a permanent contact between the central flange and the rolling bearings.

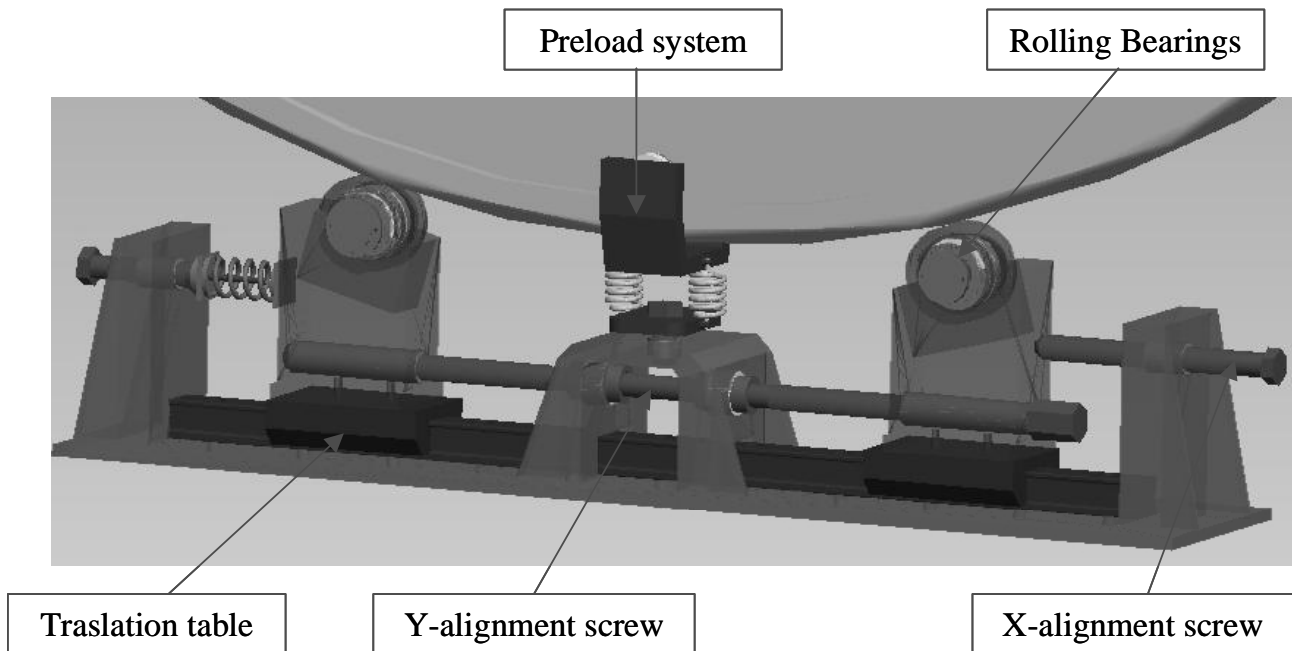


Figure 16. Nasmyth Platform Adapter
REFERENCES

1. F.J. Fuentes et al. EMIR Mechanical Design Status. *Astronomical Telescopes and Instrumentation*. (5492-75). SPIE, Glasgow, Scotland. UK. 2004.
2. D. Vukobratovich, *Advanced Topics in Opto-Mechanics*, edited by Siralimited, 1-84, 2001.
3. P.R. Hasting and D. Montgomery, Support of Cooled Components in Astronomical Instruments, *Cryogenics*, 33, N° 11, 1032-1036, 1993.
4. S. Henein, *Conception des guidages flexibles*. Presses Polytechniques. Viena, 2001.
5. A. Slocum, *Precision Machine Design*. Prentice Hall, New Jersey, 1992.