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EMIR Mechanical Design Status

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ABSTRACT

EMIR is the NIR multi-object imager and spectrograph for the GTC (Gran Telescopio Canarias). The instrument PDR phase was held successfully in March 2003, and we are at present in the middle of the ADR (Advanced Design Phase) during which a number of mechanical concepts will be tested on development prototypes to ensure the feasibility of the PDR proposed design. This presentation contains a technical description of the mechanical design of the instrument, as well as the prototypes development. The mechanical design is essentially built around the optical layout by providing an optical bench for mounting the optomechanics, the mechanisms and the detector, all this inside a custom-designed vacuum vessel and with the corresponding cooling system. One of its main design features is the use of a cryogenic reconfigurable slit mechanism to generate a multi-slit configuration, a long slit or an imaging aperture at the telescope focal plane. This feature will permit to maintain the instrument in operation conditions for a long time and take advantages in both a classically scheduled and a queued service observing schemes

Keywords: Infrared spectrograph, mechanical design, cryogenics, FEA, GTC

1. EMIR MECHANICAL CONFIGURATION

EMIR is a wide field near-infrared camera and multi-object spectrograph, covering the wavelength range 0.9-2.5 μm , with a Field of View (FOV) of 6x6 arcmin in direct imaging and 6x4 arcmin in multi object spectroscopy. EMIR is being designed to be installed in the GTC Nasmyth focus, attached to the flange of the telescope field rotator mechanism. This allows having a non-rotating object at the instrument entrance focal plane, but at the cost of having EMIR rotating during the observing run. This rotation produces image displacements on the detector due to the gravitational deformations of the mechanical structure. Image stability is a critical requirement for EMIR (the residual displacement of the image in spectroscopic mode must be less than 5.5 μm after a rotation of the instrument of 180°) and forces to use an image movement compensator, based on the movement of the detector assembly along two orthogonal axis.

The instrument optical design is described elsewhere on these proceedings^{1,2}. It is based on a fully refractive system with axial symmetry, using a classical collimator-camera configuration which provides a pupil of 100 mm in diameter, plus a field lens for flattening the GTC focal surface.

The EMIR collimator is a refractive system and consists of four lenses (CO1 to CO4) mounted on two barrels (one barrel supports CO1 and the other supports the remaining three lenses). A periscope having two flat mirrors is located between collimator lenses CO1 and CO2 to fold the optical path in order to fit the instrument to the GTC envelope and achieve a more compact design. The field lens has an optical aperture of 434 mm and a physical diameter of 470 mm. It is used as the cryostat window due to packaging and throughput considerations, but at the cost of a more complex design driven by critical requirements in terms of pressure loads, thermal loads and alignment tolerances. The configurable slit mechanism (CSU) is located on the flat focal plane provided by the field lens. It consists of a cryogenic robot that displaces sliding bars across the instrument FOV to mask unwanted light. A slit is formed at a designated position within the FOV by approaching two opposite bars and maintaining a distance between them to create a rectangular single slit. A long slit is formed by aligning several single slits along the same spectral position.

An all-refractive camera is used to focus the collimated beam on a detector. The camera consists of 6 lenses (CA1 to CA6), all spherical except for one aspheric surface. The camera EFL (effective focal length) of 191 mm allows to obtain the required detector scale (0.2 arcsec/pixel) on a flat focal plane.

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The change between the imaging and spectroscopic observing modes is done by inserting or removing the diffractive element in the pupil area of the instrument. Two dispersion components have been proposed during the evolution of the EMIR optical concept: a standard grism and a novel pseudo grism proposed by the Observatoire Astronomique de Marseille-Provence (OAMP, France) and developed by Jobin Yvon^{2,3}. The mechanical baseline has been developed assuming standard grisms will be used, but it is straightforward to modify it for the pseudo grisms. Cold stop is placed at the first surface of the grism, according to the optical beam.

Several grisms are located in the collimated beam, near the cold pupil, whereas filters are located between the camera barrel and the detector to decrease their size. Two remote controlled wheels (one for grisms and one for filters) allow the selection of the adequate combination of these elements to be used in the different observing modes.

The detector assembly is mounted on a translation unit (DTU) that allows moving it along three orthogonal axis, one for focusing and the other two for image movement compensation when the instrument rotates. The detector itself is a Hawaii-2 FPA having 2kx2k pixels. The development of the DTU (including design, manufacturing, assembly and tests) will be subcontracted from the requirements level.

All the optical elements (excluding the field lens) are mounted on a common structure (the Optical Bench, OB) which is cooled down to 77 K and mounted inside a vacuum cryostat. The OB is supported and thermally isolated from the warm structure of the cryostat by means of three Axial Support Trusses (AST) and six Radial Support Trusses (RST). The CSU, the Grism and Filter Wheels, the DTU and the detector assembly are also attached to the OB. The field lens is used as the cryostat entrance window.

The cryostat is attached to the Nasmyth rotator flange by means of the Nasmyth Rotator Adapter (NRA). 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 Nasmyth rotator and the platform.

A functional diagram of EMIR is shown in Figure 1.

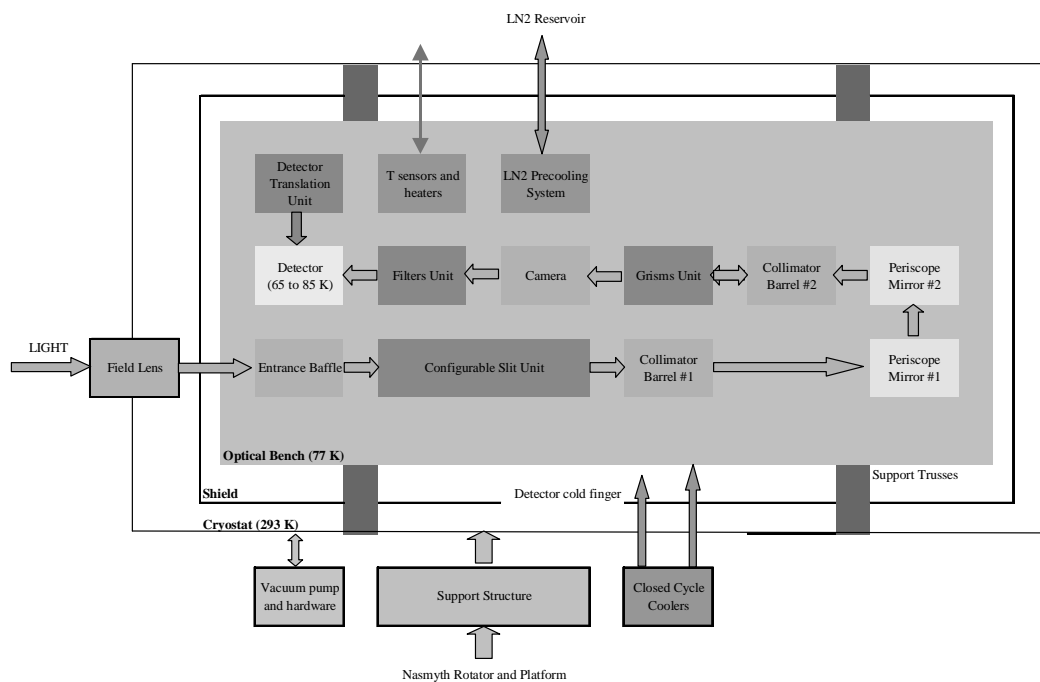


Figure 1. EMIR opto-mechanical functional diagram

EMIR is a complex instrument due to the design requirements imposed by the field size, image scale, image quality, spectral resolution, image stability and cryogenic mechanisms performance needed during scientific exploitation. Sizes of the optical components are included in Table 1, whereas main dimensions of cryogenic mechanisms are included in Table 2.

| Element | Phys. Aperture |
|---------------------|--------------------|
| Field Lens | 470 mm |
| Collimator lenses | from 190 to 490 mm |
| Periscope mirror #1 | 320x230 mm |
| Periscope mirror #2 | 270x190 mm |
| Cold stop | 113 mm |
| Grism | ~130x130x145 mm |
| Camera lenses | from 120 to 160 mm |
| Filter | 70 mm |
| Detector | 37.9x37.9 mm |

Table 1. EMIR optical components

| Mechanism | Type | Element size | Number of elements | Envelope size |
|--------------|------------------------------|----------------|-----------------------|-----------------|
| CSU | Cryogenic configurable robot | 300x300 mm FOV | 50 to 90 single slits | 1.4x0.65x0.25 m |
| Grisms Unit | Wheel | 130x130 mm | 4 grisms | φ0.6 m |
| Filters Unit | Wheel | φ70 mm | 11 filters | φ0.4 m |
| DTU | Flexure based translator | - | - | 0.3x0.3x0.2 m |

Table 2. EMIR cryogenic mechanisms

The following are the most relevant mechanical design specifications at subsystem level, obtained from the top-level requirements and the interface constraints via the system error budgets:

- Mass Limit: The total mass of the instrument shall be less than 7500 Kg, according to GTC constraints
- Nominal Working Temperature: 77 K
- Cold Optics Temperature Variations: ± 10 K
- Optical Bench Temperature Gradients: less than ± 5 K
- Cool-down Time: 96 h (TBC)
- Warm-up Time: 48 h (TBC)
- Mechanisms Reconfiguration Time: less than 5 minutes
- Field Lens Positional Tolerances: ± 2 mm decenter, ± 1.5 mrad tilt
- CO1 Positional Tolerances: ± 1 mm decenter, ± 1 mrad tilt
- CO2 to CO4 Positional Tolerances: ± 150 to ± 80 μ m decenter, ± 0.5 to ± 0.25 mrad tilt
- Camera Lenses Positional Tolerances: ± 75 μ m decenter, ± 0.2 mrad tilt
- Image Movement: The maximum image displacements of the slit image on the detector, due to gravitational deformations of the mechanical structure, shall be less than 5 μ m after an instrument rotation of 180°, assuming the image movement compensator mechanism is activated. The allocated contribution to gravitational deformations of the OB (the main contributor) is 2.5 μ m, assuming 1 μ m is allocated to the structure hysteresis
- CSU Repeatability: better than ± 160 μ m along the spatial direction and ± 16 μ m along the spectral direction
- Grism Wheel Repeatability: better than ± 0.2 mrad about three orthogonal axis
- DTU Travel for Image Stabilization: ± 185 μ m in both axis in raw mode. ± 25 μ m in fine mode
- DTU Travel for Focusing: ± 100 μ m
- DTU Resolution for Image Stabilization: 6 μ m in both axis in raw mode. 0.3 μ m in fine mode
- DTU Resolution for Focusing: 5 μ m
- DTU Repeatability for Image Stabilization: ± 10 μ m in both axis in raw mode. ± 0.5 μ m in fine mode
- DTU Repeatability for Focusing: ± 10 μ m

The mechanical layout of EMIR mounted on the Nasmyth platform is shown in Figure 2. The structural mainframe of the cylindrical cryostat is the Support Plate (SP), to which the two vacuum covers are attached. The cryostat shall be made in austenitic Stainless Steel Type 304. The alternative use of Al alloy 6061, 5083 or 2219 is under study. Other non-cylindrical geometries are also being studied. The union between the cylindrical and torispherical parts of the covers, and between them and the Support Plate, shall be reinforced to avoid stress concentration in the edges. The field lens is mounted in the torispherical front cover and works as the cryostat vacuum window. A small window is situated above the field lens for alignment purposes during the integration process. Four mechanical coolers (closed cycle coolers based on standard Gifford-McMahon cycle) are mounted on the cryostat (two on the front cover and two on the rear cover), using vibration isolating supports. A turbomolecular pump mounted on a electrically operated gate valve is directly attached to the dewar to increase the pumping efficiency. In Figure 2 appears also represented the NRA bar structure to attach the cryostat to the Nasmyth rotator and the NPA structure to support the cryostat on the Nasmyth platform. The cryostat size is 1650 mm diameter by 2260 mm length, having a useful vacuum volume of 4.5 m³. The design is carried out according to the ASME Pressure Vessel Code and finite element models in order to calculate and optimize the vessel components for the allowable pressure and the buckling loads respectively. The total mass of EMIR is 4100 Kg (3100 Kg without the Nasmyth and electronics supports), being 2000 Kg the mass of the cryostat, 800 Kg the mass of the OB, 100 Kg the mass of the lens barrels, 50 Kg the mass of the periscope and 150 Kg the mass of the mechanisms.

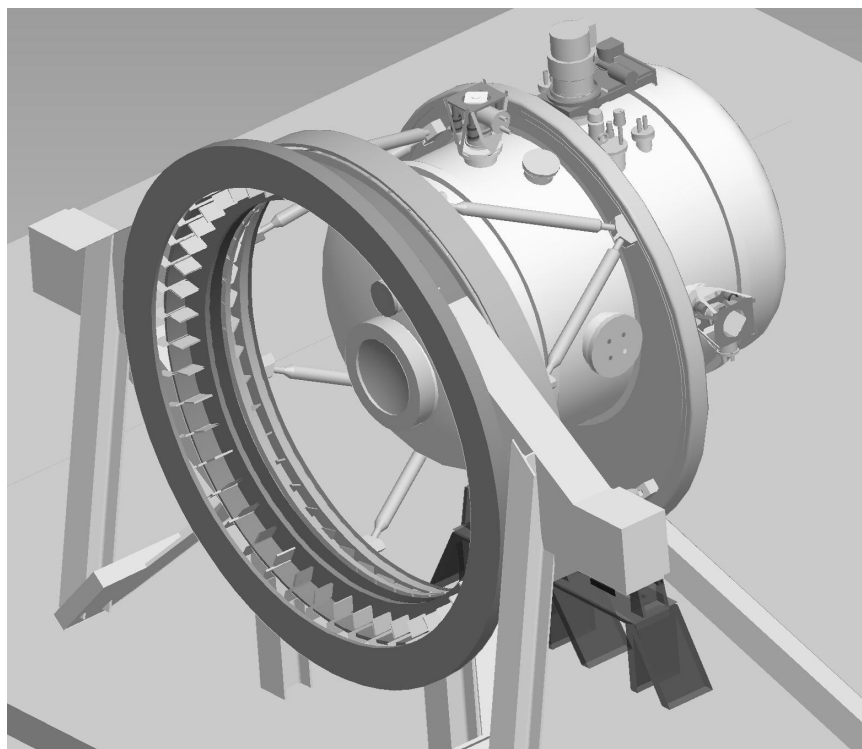


Figure 2. EMIR mechanical layout on GTC Nasmyth platform

1.1 Mechanical Structure

The components of the EMIR mechanical structure are shown in detail in Figure 3. The mechanisms and optical components (except for the field lens) are attached to the OB and cooled to 77 K. The OB is supported by the cryostat Support Plate (SP) by means of the Axial and Radial Support Trusses, and the SP is attached to the Nasmyth rotator and platform by means of the NRA and the NPA. A detailed description of each component is included elsewhere on these proceedings⁴

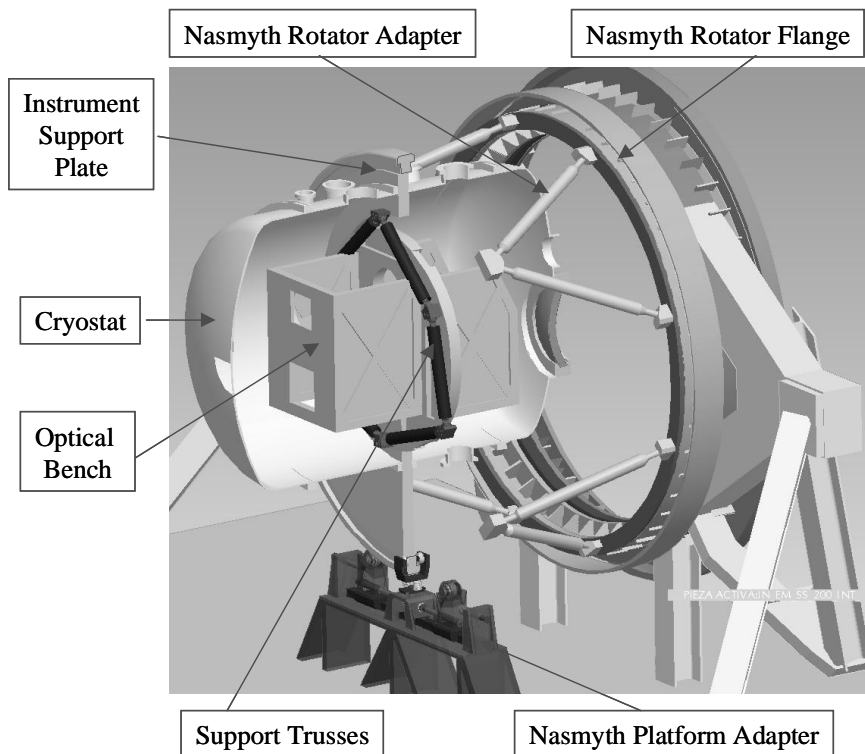


Figure 3. EMIR mechanical structure

1.2 Cooling System

Three different temperature levels must be reached and maintained inside the cryostat: 77 K (± 10 K) in the OB, the cold optics and the mechanisms, ~ 70 K in the detector and ~ 40 K in the cold getter, with a nominal room temperature of 281.5 K (± 10.5 K). Higher room temperatures in the IAC test laboratory have also been taken into account within the thermal model. EMIR will use liquid nitrogen (LN₂) for precooling and four two-stage mechanical coolers to maintain the cold components at the nominal working temperature. According to the thermal model, about 1500 l of LN₂ will be needed to precool EMIR, and a cooling capacity of about 55 W is needed on the first stage of each cooler, assuming the Support Trusses are made from G10 and a thermal shield MLI covered is used.

Four options are being considered for precooling:

- LN₂ tanks directly conformed on the OB
- LN₂ tanks directly attached to the OB
- LN₂ cooling loop with pipes directly attached to the OB
- LN₂ cooling loop with pipes directly welded to the OB

All of them shall:

adapt to the envelope, shape and structure of the OB
 ensure the N₂ gas purge with no danger
 ensure an adequate performance of the OB both, when cooling down and in working conditions

and should:

allow the OB to warm up by filling up with N₂ gas (as a backup option to the general warm-up system)
 facilitate the location and performance of the warm-up system
 facilitate an adequate thermal distribution all along the OB
 reduce the heat losses between the OB and the vacuum chamber
 absorb the differential contractions between the OB and the vacuum chamber with no transmission of stress or strain to the OB

Present precooling design is based on the first option, conforming the LN₂ tanks on the OB by welding and/or machining (see Figure 4), but the pros/cons of the other 3 alternatives are being evaluated.

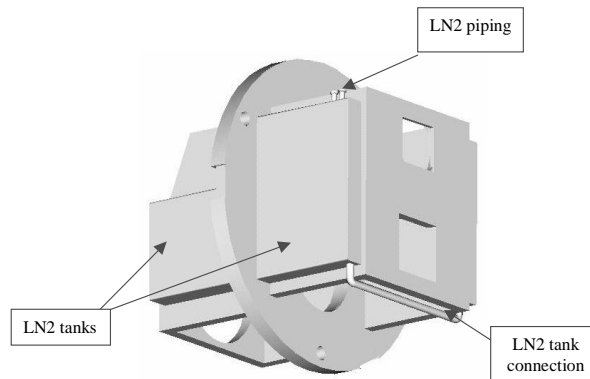


Figure 4. Precooling scheme using LN₂ tanks

1.3 Mechanical Layout

The instrument mechanical layout inside the cryostat is shown in Figure 5, where the cold optics, mechanisms and detector assembly are presented mounted on the OB. Left drawing is the bottom view of the OB, showing the CSU mounted on the OB front surface (according to the optical beam), the first collimator barrel and the periscope at the OB rear surface. Right drawing is the upper view of the OB, showing the second collimator barrel, the grism wheel with the housing removed to show the grism assemblies, the camera assembly attached to the hole between the two pockets on the OB, the filter wheel and the DTU supporting the detector assembly.

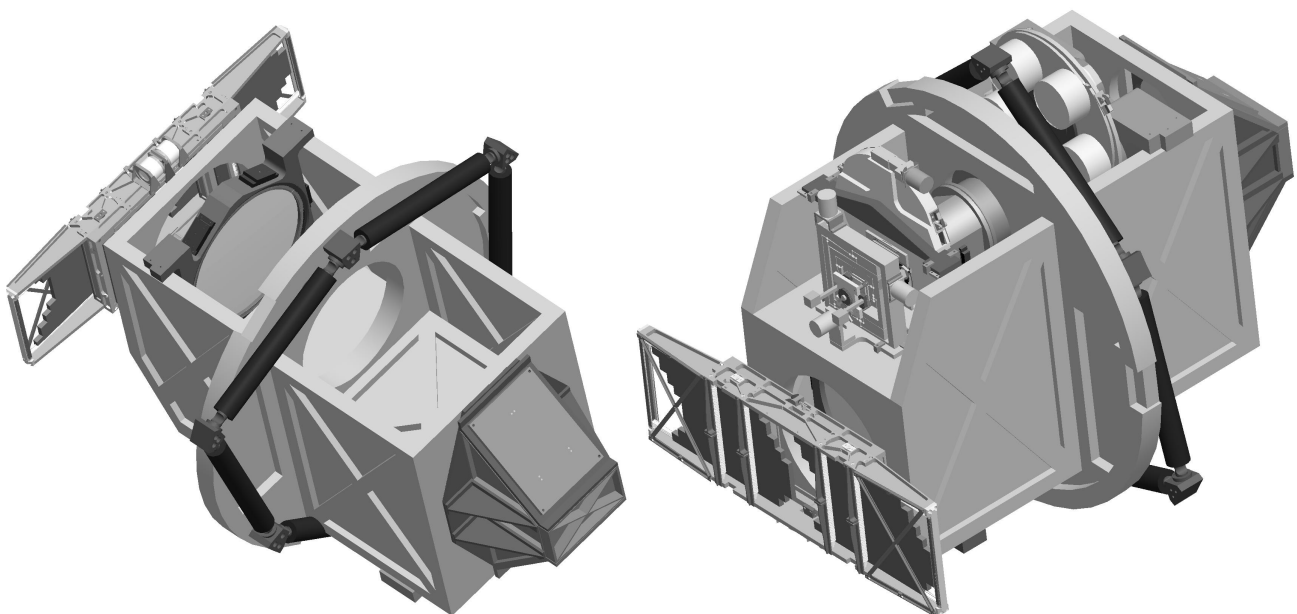


Figure 5. Two views of the EMIR Optical Bench, with all the cold components mounted inside

1.4 Collimator and Camera Barrels

Two barrels are being designed to support the collimator lenses, one for CO1 and the other for CO2 to CO4, whereas a single barrel encloses the six camera lenses. The second collimator barrel and the camera barrel use a standard radial positioning system having two fixed reference surfaces and a spring loaded radial support. Three different radial support concepts have been proposed for the first collimator barrel, having from 3 to 6 contact surfaces and different combinations of fixed and preloaded supports. The concept used for radial loaded supports and axial support is presented in Figure 6. A detailed description of the design proposed to support mechanically the EMIR cold lenses is included elsewhere on these proceedings⁵

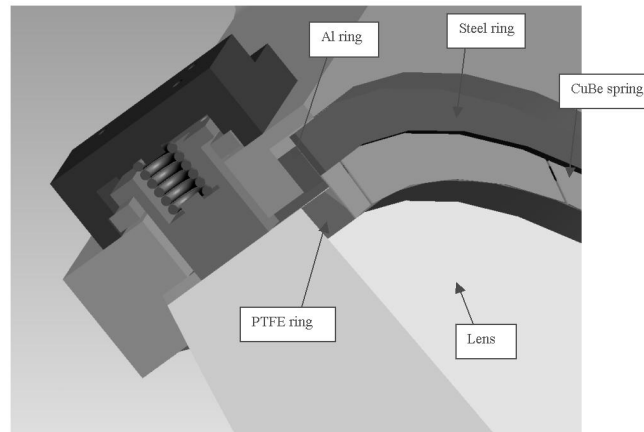


Figure 6. EMIR cold lenses radial and axial support concept

1.5 Configurable Slit Unit

The CSU concept is based on a number of sliding bars that move on the focal plane, being a single slit made by two opposite bars. Long slit is configured aligning all the bars on the same position on the field, and image mode is obtained parking the bars outside the field. The CSU concept is presented in Figure 7, based on a previous conceptual design made by the Swiss company CSEM with whom we signed a contract during the Preliminary Design phase. The final contract for the procurement of the CSU is at present on the process of public tendering.

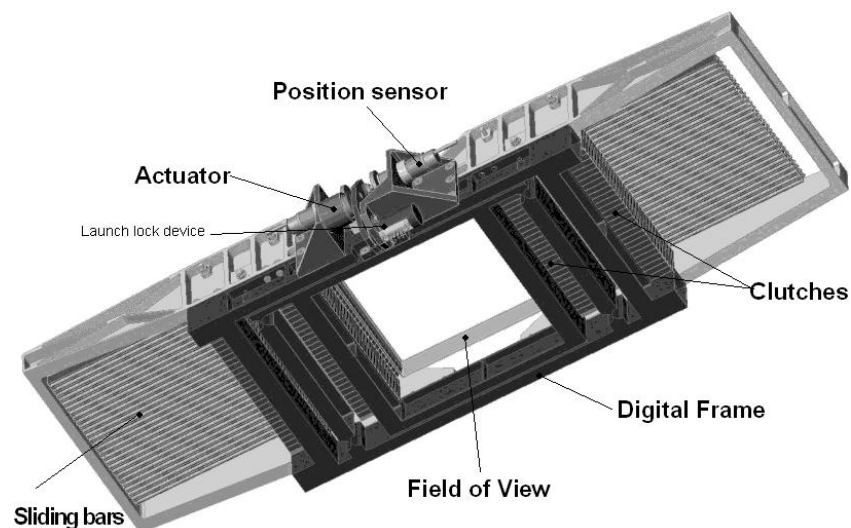


Figure 7. CSU general concept

1.6 Grism and Filter Wheels

Up to four grisms and an open position are mounted on a rotating wheel having an external diameter of 550 mm. A drawing of the wheel is shown on the left side of Figure 8, including the housing cover, the wheel, the drive unit, and the grism mounted in the mechanical holders. The filter wheel is smaller (400 mm diameter) but it is based on the same concept. It appears represented on the right side of the same figure.

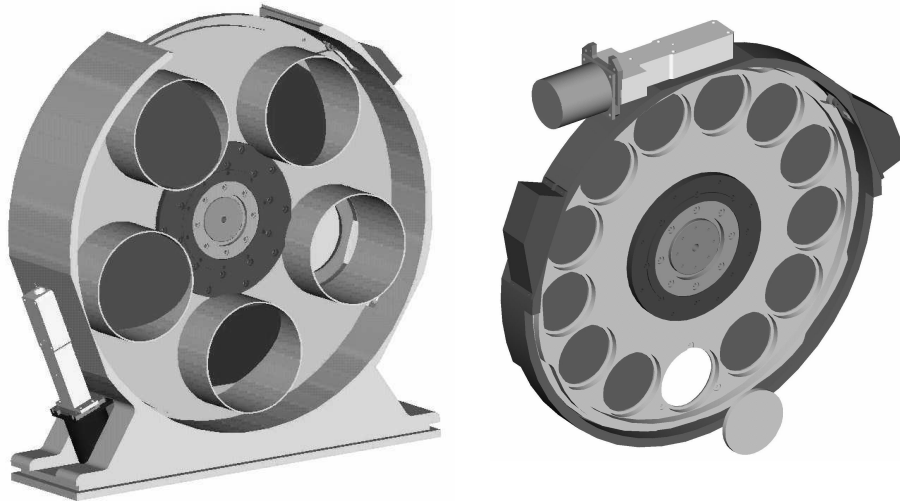


Figure 8. Layout of EMIR grism and filter wheels

EMIR wheels concept is based on similar mechanisms made at the IAC for LIRIS, a near infrared spectrograph now fully operational at the Cassegrain station of the William Herschel 4.2 m Telescope in Roque de los Muchachos Observatory (La Palma, Canary Islands). Wheels are driven via a cryogenic stepper motor (made by Phytron) that turns a worm which engages the gear machined in the wheel perimeter. The wheel is able to rotate an infinite amount of degrees (that is, there are no end stops). The worm is made from DuPont Vespel SP3, a polyimide material loaded with MoS_2 which makes it self-lubricating in cryogenic conditions. The worm is carried on a shaft which is supported on either side of the worm by radial ball bearings which are manufactured for cryogenic use. The bearings are carried in an aluminium housing which also serves to carry the drive motor. The housing forms a light-tight closure to the access port which enables the worm to mesh with the wheel. (see Figure 9)

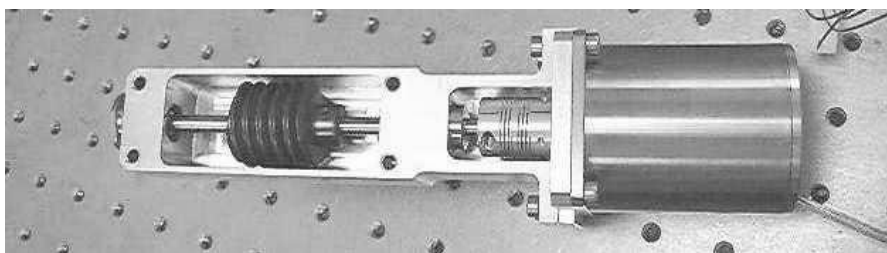


Figure 9. Detail of wheel drive units, showing the cryogenic motor, the worm and the housing

The existing design of LIRIS wheels is being optimized to relax the requirements of the supporting bearings, increase the thermal path to cool the unit and introduce a controlled friction torque that allows to position the wheel counting motor steps with the required repeatability. The new concept is based on the use of a single angular contact bearing of small dimensions as a radial constrainer, together with a friction plain bearing that constraints the wheel axial and tilt displacements, generates the friction torque to avoid backlash and provide brake torque during observation and provides

a cooling path (see Figure 10). The plain bearing should employ dry lubrication to survive the friction wear in a cryogenic environment. Several materials (Al, Bronze, stainless steel, PTFE, Vespel) and surface treatments (Dicronite, Nituff) will be cold tested to select the optimum design of the dry lubricated interface.

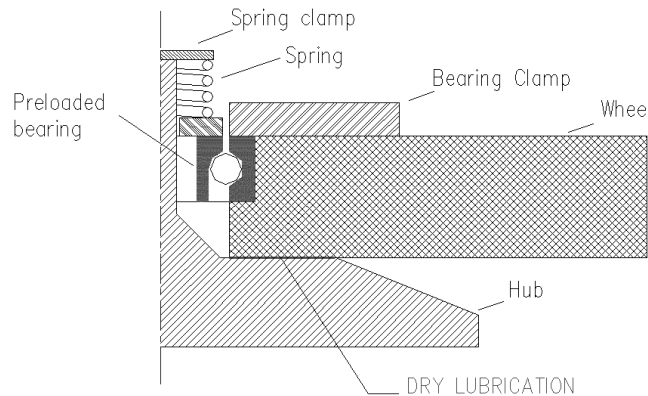


Figure 10. Wheels support, including the cooling path and friction torque concepts

2. DEVELOPMENT PROTOTYPES

A number of critical concepts to be validated with functionality and performance tests made on development models were identified on the Risk Analysis presented at the PDR. A risk mitigation plan has been prepared according to the conclusions of that analysis, including the definition and scope of the prototypes to be tested, the tests to be made according to the requirements to be validated and the prototype test schedule. A list with the prototypes being developed and the tests to be performed is included in Table 3.

Test #1 is aimed to increase our knowledge of surface finishing needed on critical components at low temperatures.

Test #2 is aimed to select the design of the thermal links between the mechanical coolers and the cold components.

Test #3 is designed to measure the cold performance of each stepper motor received from Phytron, measure the MTBF and validate the requested useful life. Figure 11 shows the test bench for motor validation.

Test #4 is aimed to validate the proposed design of axial and radial support trusses, as they are critical components that support all the cold mass under demanding conditions of stress, gravitational loads and temperature gradients. The prototype will be representative of the full design concept (including the bonded joints between the G10 trusses and the steel flexures⁴), but the geometry will be scaled 1:2 to adapt the total size to the existing bench for cold testing. Tests include measurements at room temperature of the mechanical properties of the bonded interface, survival to thermal cycling, relative displacements when cooling from room temperature to 77 K (athermalization) and displacements when the whole system rotates⁴

Test #5 includes a number of tests to validate the feasibility of having radial supports bonded directly to cold lenses, according to a previous design already discarded. Previous results showed that bonded joints can break if temperature gradients are not well controlled. No more tests have been done on this concept.

Test #6 is aimed to validate the final design to be used for the barrel of the first collimator lens, and specifically to select one of the three radial support concepts proposed. A detailed description of prototypes and tests to be performed is included elsewhere on these proceedings⁵. Figure 12 shows the mechanical barrel to be used during tests.

Test #7 is aimed to validate the proposed concept for wheels support (see 1.6), including the functional requirements, the thermal conductance, the friction torque and the design options for the dry lubrication of the contact interface.

Test #8 is aimed to validate the final design used for both wheels. The prototype (see Figure 13) will be representative of the final grism wheel, using mass dummies instead of grisms. The mechanism repeatability, changeover time, reset time, temperature profile during cool-down and MTBF will be measured at working temperature during tests.

All tests will be performed and results documented and linked to the design during the present ADR phase.

| No | Concept to be validated | Tests | Prototype |
|----|--|--|--|
| 1 | Cryo-materials | Outgassing & Conductance | Material samples |
| 2 | Thermal links | Typology | Proposed design alternatives |
| 3 | Cryo motors | Torque vs. Speed, MTBF | Phytron cryogenic motors |
| 4 | Support Trusses | Athermalization, deformation under gravitational loads and survival to thermal cycling | Final design scaled 1:2 |
| 5 | Lens barrel radial support. Bonded concept | Cryogenic adhesive bonding survival to thermal cycling | Bonded samples |
| 6 | Collimator Barrel #1 | Functionality. Positional tolerances. Gravitational displacements. Cooling profile | Final design with the proposed alternatives for radial support |
| 7 | Wheel bearings | Cold performances | Proposed design alternative |
| 8 | Grism wheel | Functionality and mechanism performances | Final design |
| 9 | CSU | Functionality and cold performances | Final concept simplified, using only 4 bars |

Table 3. Development models definition.



Figure 11. Cryo motors test bench

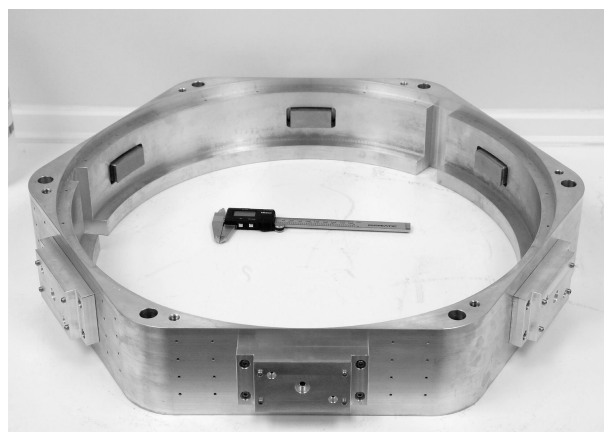


Figure 12. Collimator barrel #1. Prototype components

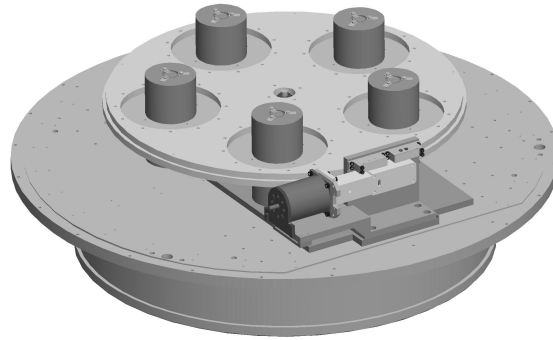


Figure 13. Grism wheel prototype mounted on the cold bench for tests

A specific test cryostat (EMIR Multipurpose Cryogenic Test System, EMCTS) has been designed and is being made at the mechanical workshop of TTM in Valencia (Spain). The intention is to have a versatile test cold bench to perform tests #4, #8 and #9 during this ADR phase, as well as to perform final cold mechanical and optical tests on the CSU, Grism Wheel, DTU, Camera Assembly and Collimator Barrels.

The EMCTS has the following operation specifications:

- Dewar size: $\phi 960 \times 900$ mm
- Useful cold space: $\phi 800 \times 400$ mm
- Number of windows: 3 of different sizes ($\phi 440$ mm max)
- Handling: The cryostat will operate in horizontal and vertical position. It will be possible to rotate it 360° around the symmetry axis during tests using a commercial rotator
- Precooling: using the LN2 tank attached to the cold plate
- Coolers: 2 Leybold Coolpower 5/100 2 stages Closed Cycle Coolers, using one compressor Leybold Coolpak 600D for dual operation

The EMCTS is on the final stages of manufacturing. Assembly, vacuum and cold tests will be performed next July 2004 and the cryostat will be sent to the IAC before August. Figure 14 is a 3D model of the full system, including the front window and the lateral windows, the two mechanical coolers situated on its rear part, the four supporting legs and the two extensions to test the CSU when ready. Figure 15 is a picture of the present manufacturing stage of central body.



Figure 14. EMIR test cryostat. General view



Figure 15. EMCTS main body under manufacturing

The EMIR ADR milestone is scheduled for the end of 2004, once the prototyping phase is finished and fully documented. The EMIR detailed design will start after that review. The commissioning at telescope is scheduled for 2006

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