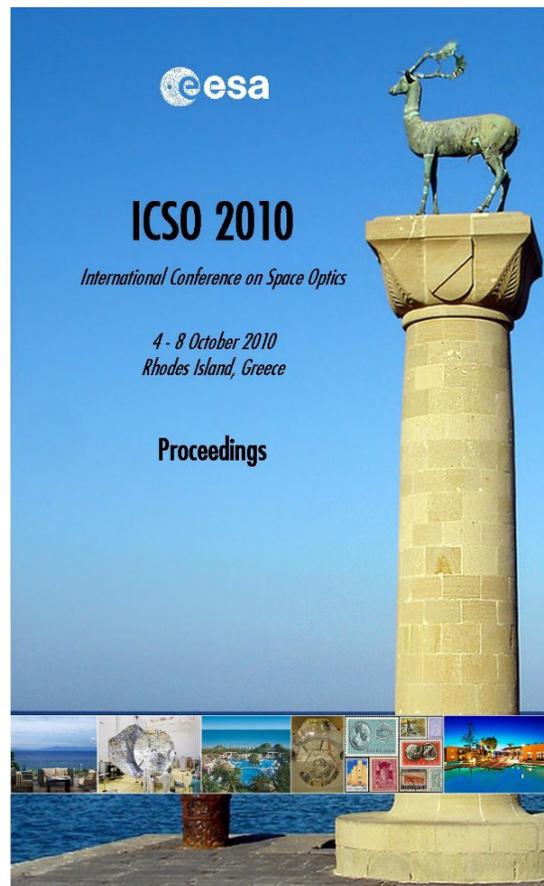


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## PRECISION MECHANISMS FOR OPTICS IN A VACUUM CRYOGENIC ENVIRONMENT

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### ABSTRACT

To achieve superb stability in cryogenic optical systems, NOVA-ASTRON generally designs optical instruments on the basis of a 'no adjustments' philosophy. This means that in principle no corrections are possible after assembly. The alignment precision and consequently the performance of the instrument is guaranteed from the design, the tolerance analysis and the detailed knowledge of the material behavior and manufacturing process. This resulted in a higher degree of integrated optomechanical-cryogenic design with fewer parts, but with a higher part complexity. The 'no adjustments' strategy is successful because in the end the risk on instrument performance and project delays is much reduced. Astronomical instrument specifications have become more challenging over the years. Recent designs of the European Southern Observatory Very Large Telescope Interferometer (ESO VLTI) 4 Telescope combiner MATISSE include hundreds of optical components in a cryogenic environment. Despite the large number of optical components the alignment accuracy and stability requirements are in the order of nanometers. The 'no adjustments' philosophy would be too costly in this case, because all components would need to meet extremely tight manufacturing specifications. These specifications can be relaxed dramatically if cryogenic mechanisms are used for alignment. Several mechanisms have been developed: a tip-tilt mirror mechanism, an optical path distance mechanism, a slider mechanism, a bistable cryogenic shutter and a mirror mounting clip. Key aspects of these mechanisms are that the optical element and mechanism are combined in a compact single component, driven by e.g. self braking piezo actuators in order to hold position without power. The design, realization and test results of several mechanisms are presented in this paper.

### I. INTRODUCTION

The Very Large Telescope of the European Southern Observatory (ESO) has capabilities for mid-infrared interferometry with the MIDI<sup>1</sup> instrument combining the signal of two telescopes. MATISSE<sup>1,2</sup> will combine up to 4 telescopes simultaneously and for the very first time allow image reconstruction. In addition, MATISSE will have a larger spectral coverage: from 2.8 to 15  $\mu\text{m}$  including interferometric spectroscopy with three different spectroscopic resolutions in the range of  $R \sim 30$  to 1000.

MATISSE consists of a few major subsystems:

- A Warm Optics Subsystem, providing the interface to the VLTI and splitting the light in the shorter wavelength L&M band and the longer wavelength N band.
- Two Cold Optics Subsystems, one for the L&M band and one for the N band.
- Two Cryostats containing the Cold Optics, one for the L&M band and one for the N band.
- Two Focal Plane Arrays, one for the L&M band and one for the N band, including the corresponding Electronics and Software.

This paper focuses on the precision mechanisms in the cold optics subsystem.

#### A. Cold Optics Performance Requirements and MAIT approach

In order to reduce thermal background radiation, the MATISSE cold optics interferometer operates under cryogenic and vacuum conditions at 40K. Alignment requirements of the optical components are very tight as every single optical component must be correctly aligned better than 0.5 arcsecond, corresponding to about 50 nm tolerance on the mounting surfaces of the optics. These specifications are challenging and cannot be obtained with the successful "no adjustment philosophy" that is generally used at NOVA-ASTRON for cryogenic instrumentation. The large number of components in the system makes traditional iterative alignment very costly and risky. The necessary adjustments will be achieved by newly designed Tip-Tilt Mechanisms for each telescope beam and a Tip-Tilt-Focus mechanism on the detector. These will be able to function in cryogenic operational conditions but are not intended to be used actively during operation.

### *B. Motorized Cryogenic functions*

For the moving mechanisms in the cryostat, one could opt for using ambient (warm) motors and rotation or translation vacuum feedthroughs. These vacuum feedthroughs have several disadvantages though. Thermal decoupling extensions are required to avoid heat injection in the cold system. Furthermore, a reliable mechanical coupling between cryogenic mechanism and feedthrough has to be established. This coupling must allow for the shrinkage difference in all directions between the warm and cold condition of the instrument and shall not compromise assembly and disassembly of the instrument.

In MIDI 8 warm motors and vacuum feedthroughs were used in order to operate as many degrees of freedom in e.g. focus mechanisms and filter wheel mechanisms. In MATISSE the number of degrees of freedom in cryogenic mechanisms increases to about a hundred. Using warm motors and vacuum feedthroughs would be very impractical and error prone. Coupled to the increased maturity of cryogenic actuators, it is decided that cryogenic mechanisms in MATISSE are equipped with cryogenic motors.

We distinguish two types of motorized cryogenic functions with different requirements: Continuous operation Functions and Alignment Functions.

Some mechanisms are used continuously during operation. This is the case for shutters, the slit selection mechanism, the photometric slider and the (filter) wheels. Key requirements for these mechanisms are reliability and repeatability. These functions are controlled by standard ESO electronics and the VLTI observation software. This standard prefers DC motors with encoder feedback, but under some restrictions stepper motors are also acceptable.

Other mechanisms are used only once during alignment. This is the case for focus and alignment mechanisms. Key requirement for these mechanisms is stability without power. The cold position may differ slightly from the warm position as there is still no need for realignment as long as the mechanism returns to exactly the same position when cold after a warm-up. Alignment functions can be controlled by offline electronics, so compatibility is less of an issue. The motors used here are preferably small, such as Piezo motors.

## II ALIGNMENT MECHANISMS

### *A. Tip-Tilt Mirror mechanism*

A large number (16) of equal modules is foreseen to control beam positioning and beam pointing in the cold optics. These modules are called the Tip-Tilt Mechanism (TTM). The TTM basically consist of a rectangular mirror with typical dimensions of 33 x 33 mm and a baseline thickness of about 8 mm. Tip and tilt of the mirror should be manipulated with microrad's resolution within a range of several millirad's. Operation should be possible in both ambient as cryogenic (30K – 100K) environment, though final use will be in the cryogenic environment. Once aligned the mechanism shall maintain its position powerless during operation.

A design for this mechanism has been developed and tested [3]. Distinctive characteristics of the concept are:

- The concept enables to implement large reduction between actuator input movement and mirror output movement. This enables less demanding use of actuator with respect to actuation force, displacement resolution and position stability. The mechanism is driven by self braking Piezo motors.
- Rx and Ry actuation is completely integrated in the design; no stacked layout. This enables a monolithic manufacturing approach for the mechanism which is beneficial for stability performance.
- Rx and Ry actuation are orthogonal; each actuator is directly linked to a single output rotation without disturbing the other output rotation.
- Mirror and mechanism are monolithic designed for optimal stability, resulting in a homogenic cooled mirror and a small cross-section, while avoiding additional construction parts. Direct aluminum polishing (details see [4]) is needed for the mirror surface

Cryogenic functional tests show that the TTM reproduces perfectly, even at temperatures of 20K. Initial test results are condensed in [3]. The latest results are available with the author.

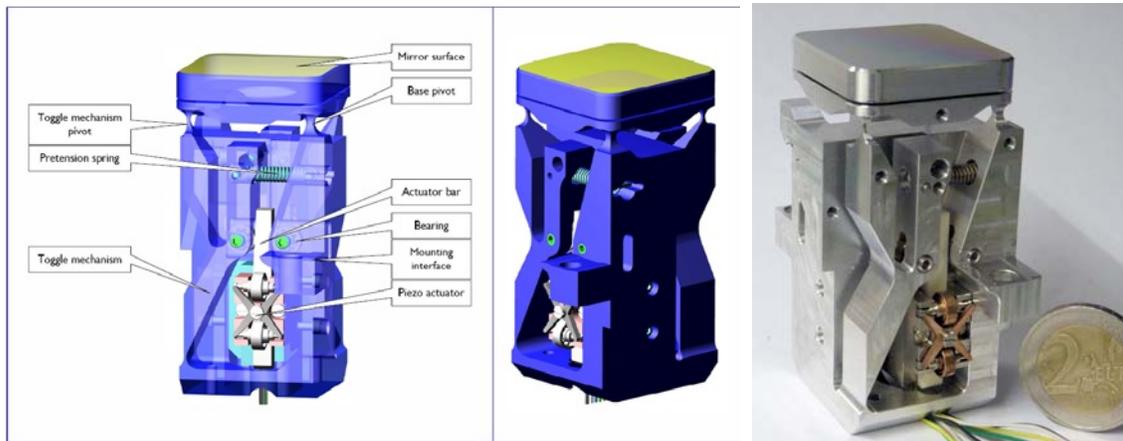


Figure 1 Tip-Tilt Mechanism including piezo motors

*B. Cryogenic Optical Path Difference correction mechanism*

The Cryogenic Optical Path Difference correction mechanism design is based on the Tip-Tilt mechanism. The OPD mechanism does not move linearly, but rotates a set of perpendicular mirrors around a hinge, which is far simpler than creating a linear mechanism for such a short range. The non-linear behavior is not a problem as the minimum OPD step size possible with this mechanism will easily be below  $1 \mu\text{m}$ . The range is limited to  $\pm 1 \text{ mm}$ , which is sufficient to compensate positional errors in cold optics due to manufacturing. In total 12 OPD mechanisms were planned for usage in the MATISSE, but none are needed after a concept update.

*C. Detector Tip-Tilt-Focus Mechanism*

A Tip-Tilt-Focus (TTF) adjustment mechanism is used to position the detector accurately at the best focus position. This mechanism has been implemented in previous instruments developed by NOVA-ASTRON, however it was never motorized. This resulted in a painstaking process to find the best focus, because a full warm-up – cool-down cycle is needed to make adjustments to the detector position.

Generally several adjustment cycles are necessary to find best focus. In MATISSE a motorized adjustment system that can run in the cryogenic environment is used. The actuators (3 in number) will be the same as used in the TTM. It will be used rather infrequently: after instrument integration for the initial detector alignment and in case of a detector upgrade.

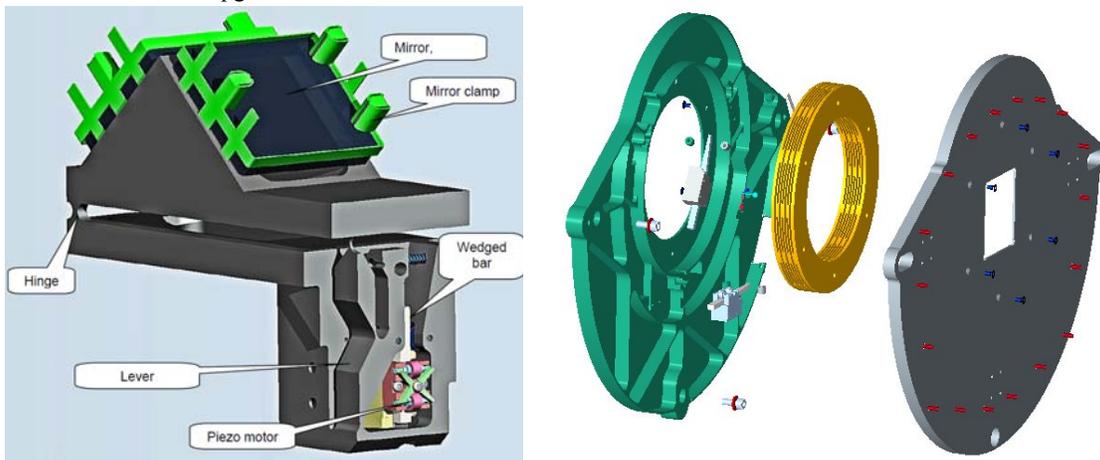


Figure 2 Left: Cryogenic Optical Path Difference correction mechanism. Right: Design of the Tip/tilt/focus mechanism. The mounting plate (turquoise) is placed right after the camera. Three motors control the distance and tip-tilt of the detector mounting plate (gray), while the spring (yellow) applies a necessary force on the motors to maintain the detector mounting plate in position.

*D. Other solutions supporting quick alignment: Mirror clip*

The mirror clip reduces assembly time significantly. The mirror clip is introduced as an idea to reduce the number of parts, risks and time spent on assembly of the large number of small optical elements. Prototypes have been developed for operational and cryogenic testing.

The mirror clip provides isostatic kinematic mounting for flat optical elements such as folding mirrors or beam splitters. 3 accurately machined mounting pads on the structure ensure that the optical element is well aligned. This peripheral mounting has several advantages: numerous optical elements can be mounted on a single structure that is relatively easy to manufacture to high accuracy, accessibility is guaranteed during integration and a single element provides superior stability in operation.

The design is a two stage assembly. The optical element is mounted in a mirror cell. Leaf springs provide sufficient force to keep the optical element locked in its position. The mirror cell provides some protection to the optical surfaces when handling and storing the mirror assembly until integration in the instrument. The cage provides a spring blade clamp to both the structure as well as to the mirror cell. During integration the mirror cell assembly is clipped into red cage with auditive, visual and sensitive feedback when the mirror cell is placed well. The mounting process is self aligning, doesn't require any tooling and is done single handed. Removal or exchange of the mirror cell assembly is easy as release levers are integrated into the cage.

Advantages:

- isostatic kinematic mounting
- one hand, single click mounting
- optics protected inside cell
- fast assembly
- no tools required

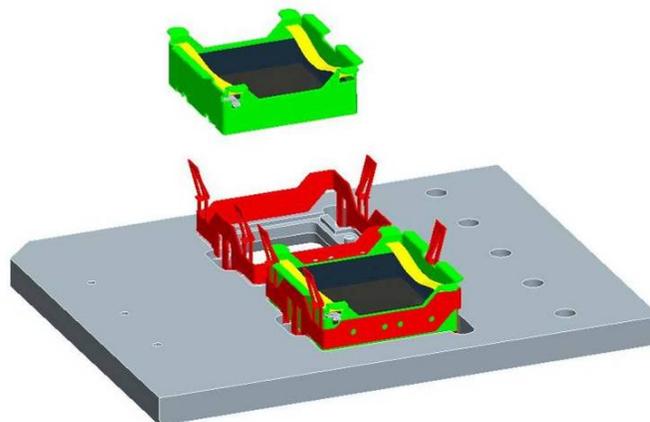


Figure 3 Mirror Clip design with the mounting structure (grey), the optical element (black), the mirror cell (green), leaf springs (yellow) and the cage (red).

III. OPERATIONAL MECHANISMS

*A. Cold Shutter*

The design of the cold shutter for MATISSE is based on an existing design by SRON (details see [5]). It has been adapted to the MATISSE requirements and the limited space envelope inside the re-imager box. It is a bi-stable mechanism with crossed leaf springs as flexural pivots. The shutter switches from one state to the other by a pulse from one of the solenoids and an opposite charged pulse of the other solenoid. The shutter is fixed in either state by the static magnetic field generated by permanent magnets so no additional power is required. The design of the moving parts is balanced so the dynamical properties of the shutter are not affected by its gravitational mounting orientation. For the given footprint and with the current setup an angular movement of 8 degrees is needed between the stable positions. In Figure 4, the shutter blade is shown in two positions to have an idea of both stable positions of the mechanism.

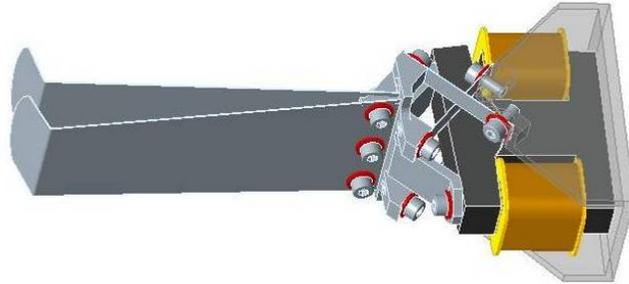


Figure 4 Design of the Cold Shutter

Four of these shutters are placed in a cassette, which can be slide into the instrument. In this way cabling can be terminated to one end of the cassette, reducing the impact on the instrument when maintenance is needed on the shutters.

#### *B. Slit Mechanism*

The baseline strategy for accurate positioning of cold mechanisms comprises the use of indents that hold a roller bearing under preload of a leaf spring (see Figure 5). Each accurate position has its own V-shaped indent.

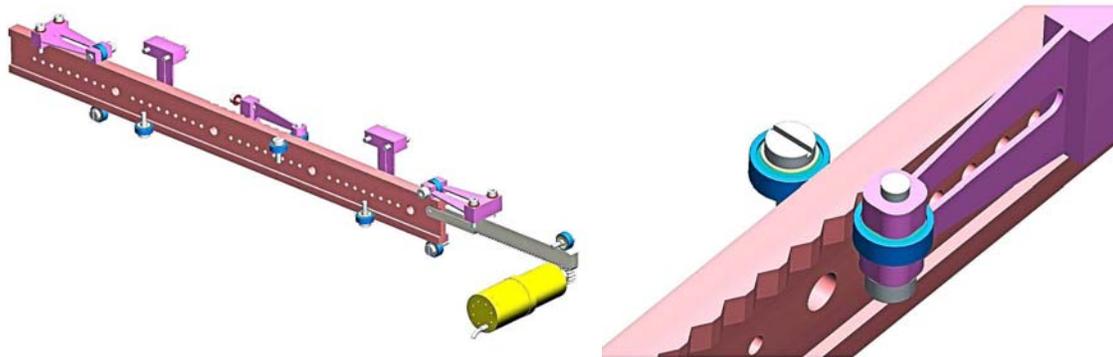


Figure 5 Design of the slit mechanism

One long slider carriage is driven by one motor. All slits are changed with a single motor movement and positioned by a mutual indent. The carriage holds all 4 channels a plate with slits and pinholes. The slit carriage is integrated in a rail structure. This structure holds the drive motor as well.

This unit can be slide into the instrument like a cartridge. In this way cabling can be terminated to one end of the unit, reducing the impact on the instrument when maintenance is needed on the slit mechanism.

#### *C. Photometric Slider*

The drive to enable highest photon fluxes while maintaining the full calibration capabilities the photometric channels of the interferometer can be switched on and off. Beam splitters mounted on a slider will be replaced by 100% reflective mirrors. The mechanism principle is the same as presented for the slit mechanism and the positioning principle has proven itself in MIDI. For this mechanism, the accuracy of positioning is of less importance, the V-grooves or indents are not used for positioning; using reference switches and a stepper motor is enough.

The slider is supported using cryogenic suitable roller bearings that have an inevitable 1 micron wobble tilting the slider slightly when repositioning, resulting in a repositioning error of the image on the detector. However, the slider configuration is such that the wobble is largest in the, less sensitive, spatial direction and smallest in spectral direction. An important remark is that this wobble affects the position of the interferogram as a whole and does not change the relative positions of the individual telescopes that form the interferogram.

#### *D. Filter Wheels*

In MATISSE 3 Filter wheels are needed with 6 positions each for bandpass filters, polarization filters and dispersion elements. Generally filters do not need to be aligned very accurate. In the case of MATISSE the filters do not have a flat substrate, but a prism to straylight problems. The downside is that alignment tolerances

of prisms are really tight in 5 degrees of freedom. The wheels are supported on the circumference in order to reach the highest accuracy, limited only by tolerances in roundness of the bearings.

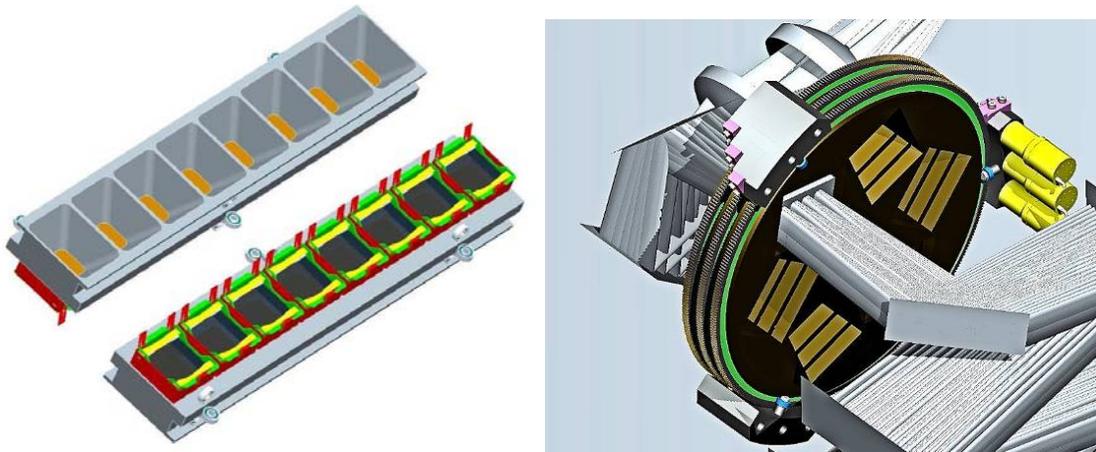


Figure 6 Left: Photometric slider using roller bearings. The figure shows front- and backside of the slider. Clearly visible are the mirror clips and the guiding ball bearings. Right: Design of 3 wheels with space for 6 optical components each.

## CONCLUSION

The techniques and solutions presented here will significantly decrease project cost and time for alignment of MATISSE. The solutions ease design requirements and reduce complexity of tolerance analyses and improve manufacturability. Project risks are reduced and although this is not required, the solutions enable alignment or performance improvements during operations after minor events, such as earthquakes.

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