

The innovative MAIT plan for the Matisse cold optics, comprising an unprecedented 220 cryogenic optical components

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ABSTRACT

MATISSE (Multi AperTure mid-Infrared SpectroScopic Experiment) will be a mid-infrared spectro-interferometer combining the beams of up to four telescopes of the European Southern Observatory Very Large Telescope Interferometer (ESO VLTI), providing phase closure and image reconstruction. Matisse will produce interferometric spectra in the LM and in the N band (2.3 to 13.5 micron) and is as such a successor of MIDI. The instrument will be developed by a consortium consisting of Observatoire de Nice (warm optics), NOVA-ASTRON (cold optics), MPI-A (cryostats) and MPIfR (detectors).

Beams of up to four Unit Telescopes or Auxiliary Telescopes (UT – AT) pass the warm pre-optics and in the cold optics all beams recombine on the detector where they create a spectral interference pattern.

An innovative MAIT plan drastically shortens the MAIT phase and therefore reduces cost. The MAIT plan comprises the assembly and alignment procedure of about 220 cryogenic optical components for which a mirror mount clip has been developed. Alignment accuracy and stability specifications are of the order of nanometers and arcsec, which requires over 50 degrees of freedom in cryogenic alignment mechanisms for e.g. Tip/Tilt and detector Tip/Tilt/Focus. The design, realization and test results of these mechanisms are presented. A cryogenic electrical switch significantly reduces the complexity of the electronic cabling and improves reliability.

Keywords: MATISSE, MAIT, cryogenic, vacuum, instrument, mechanism, mirror clip, multi pole switch, shutter

1. INTRODUCTION

1.1 Introduction

The Very Large Telescope of the European Southern Observatory (ESO) has capabilities for mid-infrared interferometry with the Mid-Infrared Interferometric Instrument for the VLTI, MIDI¹, operating since the end of the year 2002. MIDI combines the signal of two telescopes and was proven to be very successful in interferometric spectroscopic observations since it allows the comparison of the chemical composition of dust on very different spatial scales. However, the investigation of small-scale spatial structures in general, and the quantitative analysis of spectroscopic observations in particular, are strongly limited due to the small number of visibility points measured in a reasonable amount of time (over one or a few nights) and due to the lack of phase information.

MATISSE^{2,3} will combine 4 telescopes simultaneously and for the very first time allow image reconstruction of the small-scale regions traced with MIDI and thus finally allow an investigation of these structures based on an unprecedented level of constraints. On top of that MATISSE will have a higher spectral resolution and a large spectral coverage: L, M, and N bands. MATISSE will allow performing interferometric spectroscopy with three different spectroscopic resolutions in the range of R~30-1000.

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1.2 MATISSE subsystems

MATISSE consists of a few major subsystems:

- A Warm Optics Subsystem, providing the interface to the VLTI and splitting the L&M band from the 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 Manufacture Assembly Integration and Test (MAIT) aspects of the cold optics subsystem.

1.3 Cold Optics Performance Requirements

The MATISSE cold optics interferometer operates under cryogenic and vacuum conditions. Alignment requirements of the optical components are very tight as every single optical component must be correctly aligned within 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 generally used at NOVA-ASTRON for cryogenic instrumentation. Therefore some optical components have to be actively aligned.

The cold optics of predecessor MIDI was aligned warm, integrated with the cryostat and cooled down. Then it became obvious that positions and directions of beams had to be modified slightly. MIDI was warmed-up, opened and shims on mirrors were corrected. These corrections were predicted and performed with the difference of the beams on the detector between warm and cold alignment in mind. One could only investigate after cooling down whether the direction and the amount of the correction is correct. Several iterations were necessary to reach the required accuracy. Obviously, this process is time and cost ineffective, jeopardizing the quality of the instrument at every correction iteration.

In MIDI 2 telescopes interfere and for alignment this meant aligning one telescope beam to the other telescope beam. In MATISSE this is completely different as four telescopes interfere. We have to distinguish two different concepts for MATISSE:

- The abandoned ‘MATISSE pairwise PI shifter concept’ with 12 interference patterns - 2 for each telescope pair and stringent OPD requirements.
- The current ‘MATISSE Global Multiaxial concept’ with 1 interference patterns from 4 telescopes and optionally 4 photometric beams on the detector.

The MATISSE pairwise PI shifter concept was abandoned, because the OPD requirements in the PI shifter were not achievable. Still this concept is discussed here, because the MAIT approach was first tailored for this concept. In perspective to MIDI the alignment is much more complex: In total 87 degrees of freedom have to be aligned to a much tighter accuracy compared to the 2 degrees of freedom in MIDI. The MATISSE Global Multiaxial concept is much simpler in that sense. In this concept 35 degrees of freedom have to be aligned of which 8 have the highest accuracy. This paper shows that the innovative MAIT plan still offers significant benefits compared to the traditional method.

1.4 MAIT Approach

In order to avoid the alignment process used for MIDI, an approach of active adjustment during the alignment phase is designed. Active elements enable cryogenic alignment, allowing for real-time correction for fringing and position on the detector. Warm pre-alignment will only be used to position elements in an order of magnitude. Due to the large number of optics, simple mounting procedures and tools are investigated in order to cut back integration time. Strong effort is taken in the design phase to reduce the number of optical components and mechanisms. Finally, the large amount of electrical wires for temperature sensors required to monitor the stringent temperature variation requirements and the large amount of wires for the actuators forced a solution that cuts back failure in the many electrical connections.

For the whole instrument the accuracy of the position and tilt of the components depends on the manufacturing accuracy of all the mounting interfaces. Estimations show that the manufacturing tolerances will not be sufficient to build MATISSE without adjustments; especially concerning positioning of the beams on the detector. The necessary adjustments will be achieved by Tip-Tilt Mechanisms 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.

Pending Monte Carlo tolerance analyses outcome, in the present state of the design warm adjustments are foreseen on the dispersion wheels and a warm rotational adjustment around the optical axis on the detector. However subunits are mounted such that they can easily be removed and repositioned without or only limitedly influencing the alignment. Peripheral mounting of optics or mechanisms is preferred since it allows access for milling tools to the accurate positioning features for optics and it allows quick access to optics or mechanisms for inspection or repairs. This way of mounting avoids the need of opening the instrument entirely to gain access to components.

Advantages:

- Most interfaces can be produced by manufacturing accuracy
- Critical interfaces can be aligned with Tip Tilt mirrors and Tip Tilt Focus mechanism on the detector
- Simple mounting procedures cut back assembly time
- Subunits are designed such that they can be removed and repositioned in a kinematic way
- Peripheral mounting; Subunits are accessible from the outside of the instrument
- Interface of the large amount of wires is managed by multi pole switches

2. MOTORIZED CRYOGENIC FUNCTIONS

2.1 Cryogenic motors

In order to move 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. Therefore it is decided that cryogenic mechanisms in MATISSE are equipped with cryogenic motors.

We distinguish two types of motorized cryogenic functions with different requirements.

2.2 Continuous operation 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, so compatibility is also an issue. The motors used here are preferably DC motors with encoder feedback, but under some restrictions stepper motors are also possible.

2.3 Alignment Functions

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 after a warmup-cooldown cycle. 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.

3. ALIGNMENT MECHANISMS

3.1 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 consists 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 [4]. 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 separately though integrally 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 [5]) 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 [4]. The latest results are available with the author.

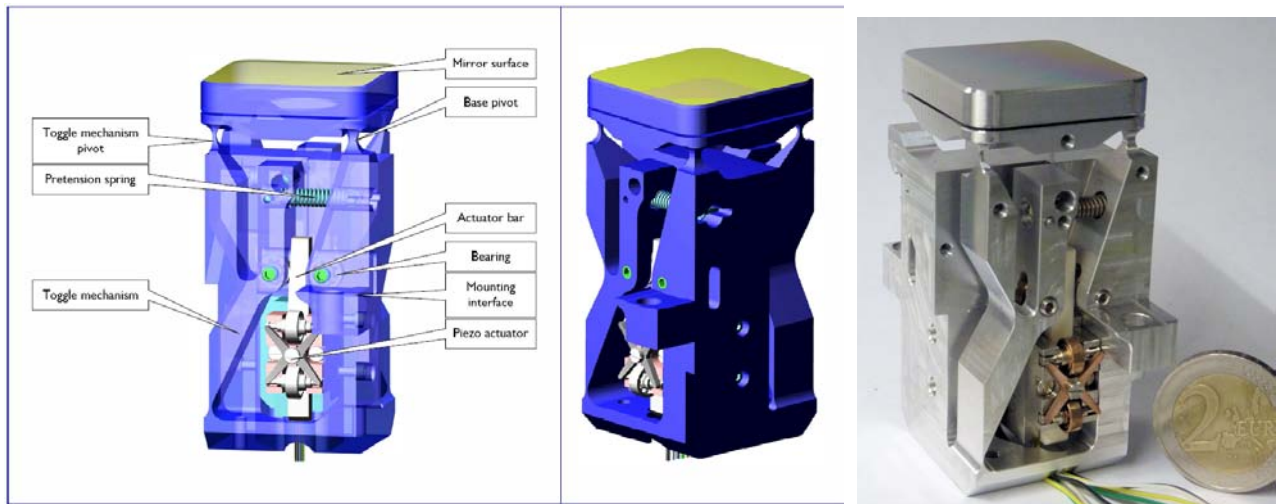


Figure 1 Tip-Tilt Mechanism including piezo motors

3.2 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 μm , The range is limited to ± 1 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 pairwise concept, but none are needed in the MATISSE global multi-axial concept. In the new concept it is sufficient to adjust the OPD correction once per telescope in the warm optics using existing mechanisms.

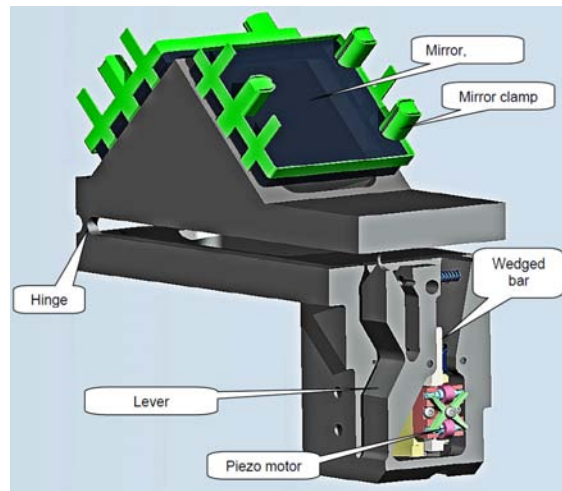


Figure 2 Cryogenic Optical Path Difference correction mechanism

3.3 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 (details see [7]), 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. The design of the test unit (see Figure 3) was for the Hawaii 2RG detector in an old housing. In MATISSE the housings of the detectors are different (smaller); however the principle is the same.

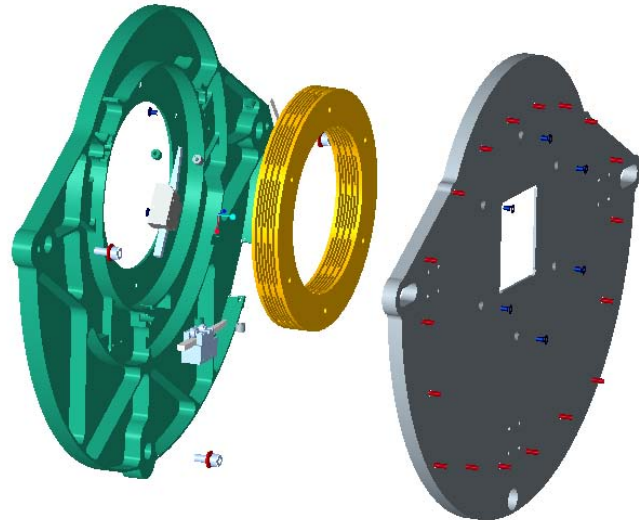


Figure 3 Design of the Tip/tilt/focus mechanism. The mounting plate (turquoise) is placed right after the camera. Three motors control the distance and tip-tilt of the detector mounting plate (gray), while the spring (yellow) applies a necessary force on the motors to maintain the detector mounting plate in position.

4. OPERATIONAL MECHANISMS

The operational mechanisms do not necessarily contribute to a shorter, more cost effective MAIT, but they are described in this paper for completeness.

4.1 Cold Shutter

An off the shelf atmospheric fast shutter will be used as high speed shutter for the remanence analysis. The fast shutter is placed just before the entrance window and the backside of this fast shutter is gold coated to reflect back into the cold environment. A read cold shutter is still needed for e.g. the 2 and 3 telescope modes

The design of the cold shutter 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 using permanent magnets so no additional power is required. The design of the moving parts is balanced so switching of the shutter is 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.

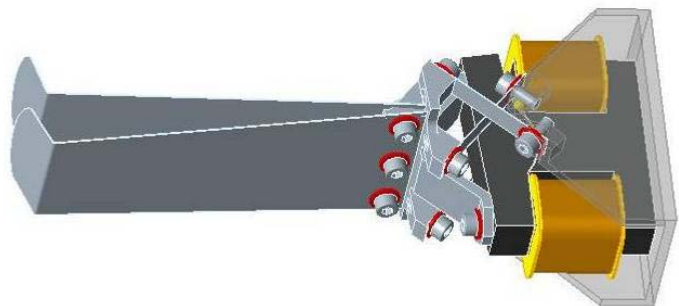


Figure 4 Design of the Cold Shutter

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.

4.2 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.

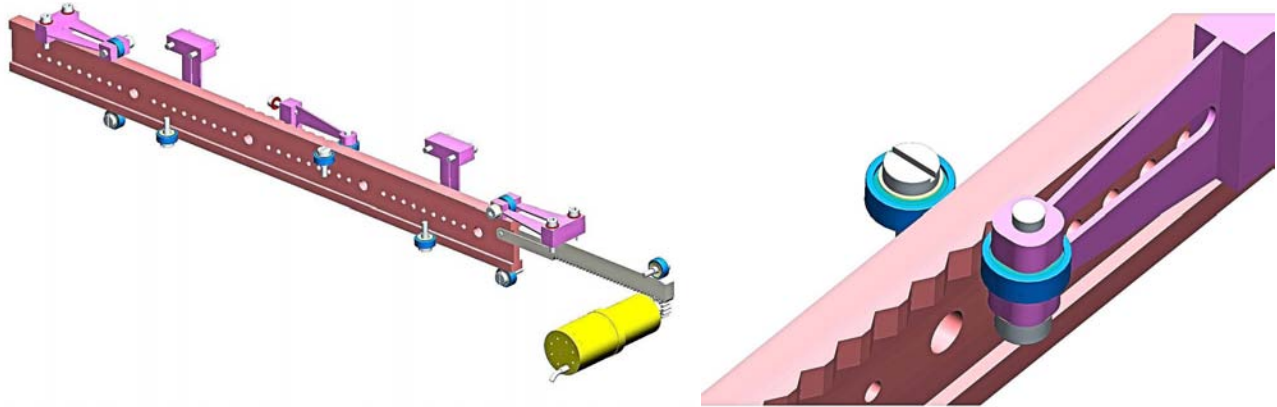


Figure 5 Design of the slit mechanism

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 on end of the unit, reducing the impact on the instrument when maintenance is needed on the slit mechanism.

4.3 Photometric Slider

As there is a demand for interferometry without photon loss, the beam splitters will be movable on a slider enabling replacement by a 100% reflective mirror. The mechanism principle is the same as presented for the slit mechanism and the positioning principle has proven itself in MIDI. As the positioning of the flat mirrors in the optical plane is of less importance, the V-groove 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 inferferogram.

The figure shows front- (beams) and backside of the slider. Clearly visible are the mirror clips and the guiding ball bearings.

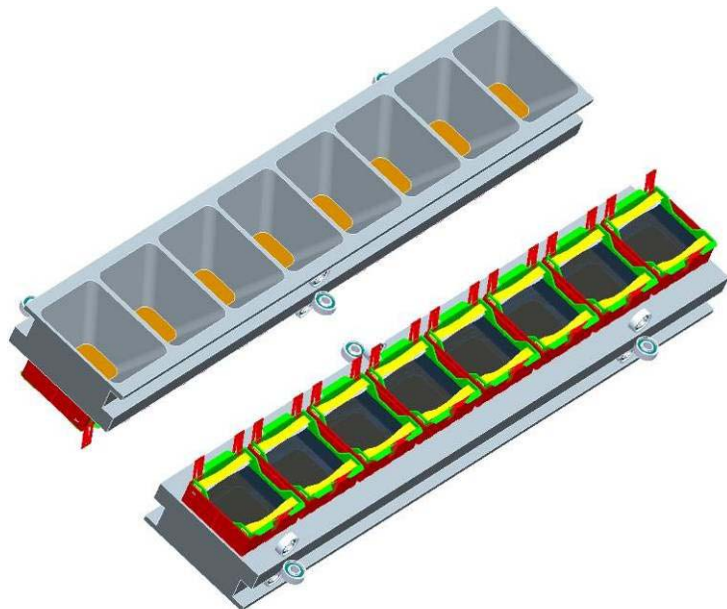


Figure 6 Photometric slider using roller bearings

4.4 Wheels

The polarization mode is accomplished by introducing a Wollaston prism in the beam, just before the grism. This splits the polarization states and doubles the number of patterns on the detector. A fourth holds optics for polarization calibration purposes. The split in the Wollaston prism is orthogonal to the spectral separation by the grism.

The picture shows only 3 wheels whereas 4 are planned in the current concept.

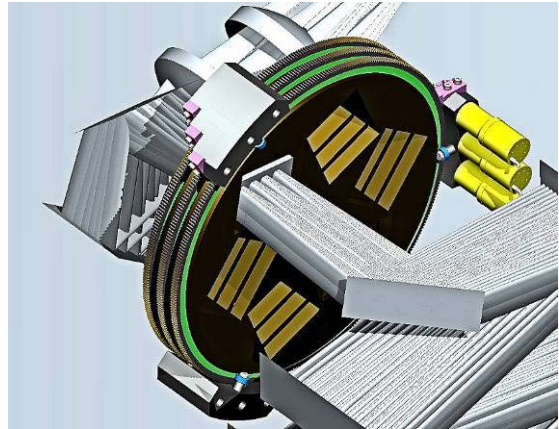


Figure 7 Design of 3 wheels with 5 optical components each.

5. MAIT SUPPORTING SOLUTIONS

5.1 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

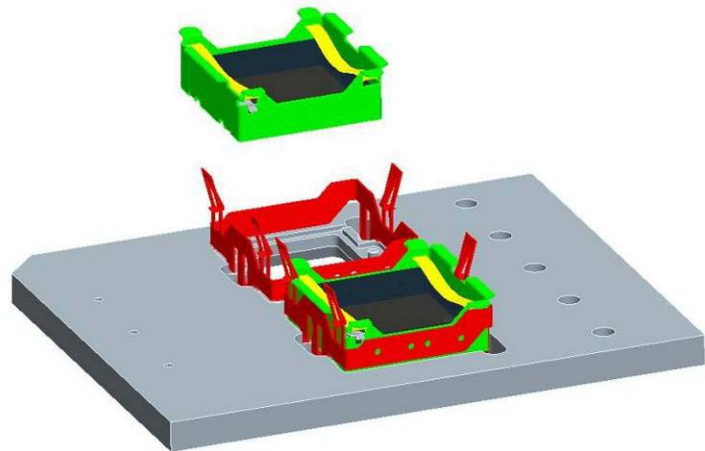


Figure 8 Mirror Clip design with the mounting structure (grey), the optical element (black), the mirror cell (green), leaf springs (yellow) and the cage (red).

5.2 Multiport switch

Cryogenic instruments are equipped with a fair amount of temperature sensors, in particular during the test phase. These RTD's are read out by a four-wire measurement for accuracy reasons. Traditionally, this would mean that all four cables are conducted thru a radiation shield and via vacuum feedthrough connections outside the cryostat. This has several disadvantages. High density vacuum feedthroughs are expensive and introduce (virtual) leaks, the thin cables are prone to break during handling or separation of instrument and cryostat and the combined copper cross section between the vacuum wall and the cryogenic instrument introduces a non negligible heat load on the cryogenic instrument.

The cryogenic multiport switch is an addressable switch, based on I2C-bus, which can switch multiple wires simultaneously. The I2C I/O expander needs 4 wires for addressing and powering the expander and 4 wires to read out on of the 16 channels. The I/O ports (up to 16) of each I2C I/O expander are controlled through the unique address (up to 128 addresses are available) of the expander. The expander controls a number of FET transistors that will be used to switch between different sensors or piezo motors. The multiport switch can be located on the fixed part of radiation shield.

Only 8 wires are needed in total for recording 16, 32 or even more temperature sensors. This compares to 8 times more wires in case of direct connections to temperature sensors. The number of wires could be doubled to get some redundancy in case of a failing wire connection. Expanders could be mounted in parallel to get redundancy in case of a failing expander. Thus for every intervention on the cryostat maximum 16 temperature sensor wires have to be disconnected.

A different application of the cryogenic multiport switch is that it can also switch between Piezo motors. Since the voltage of the motors is around 150 V, a different type of switch is required. Every Piezo motor requires 5 wires for operation, so 9 wires could operate all Piezo motors. This doubles to 18 wires when building a system with redundancy. Due to the number of Piezo motors (19 per cryostat) this compares to 190 wires using direct connections to Piezo motors.

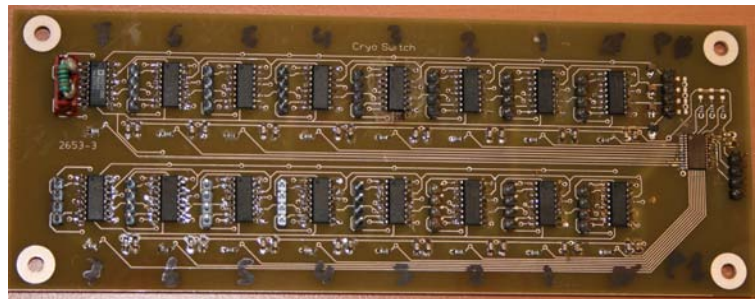
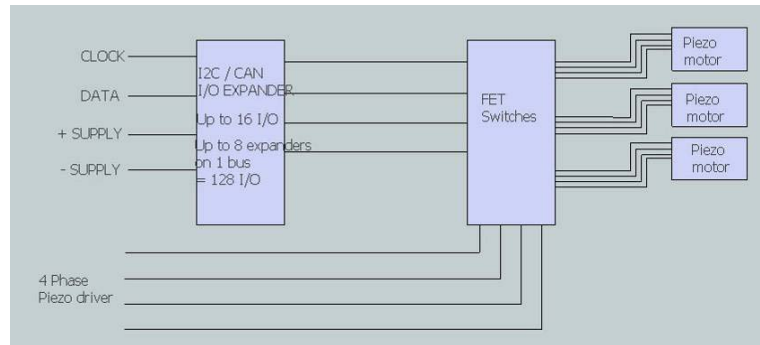


Figure 9 Schematic functional overview of the multi port switch for Piezo motors

Advantages:

- Less cabling passing the cryostat wall.
- Less heat load entering the cryostat by the cabling thermal cross section
- Less feedthrough pins needed, reducing cost and potential leaks.
- Less cabling outside the cryostat, limiting weight and connectivity check after overhauls.

6. GAIN IN MAIV IN COST & TIME

A reduction in the number of iterations that the cryostat must be opened is the most effective way to reduce MAIT cost and turnaround time. On top of that it reduces all kind of risks for the instrument, and this can be expressed in a cost and time estimation.

Not all solution described in the previous chapters are easily expressed in figures of cost and time. However, as many parameters as possible were taken into account in order to analyses the impact of MAIT design choices on project cost and time.

6.1 Approach

Several situations are compared in this analysis:

- MIDI as realized with old technology with 30 optical components and 8 degrees of freedom in cryogenic mechanisms.
- Old technology (MIDI techniques) projected on MATISSE
- New technology (reduced amount of optics / 4 channels / tip/tilt mechanisms / Multi pole switch)

Two MATISSE concepts are investigated:

- The abandoned ‘MATISSE pairwise PI shifter concept’ with 300 optical components and 108 degrees of freedom in cryogenic mechanisms.
- The current ‘MATISSE Global Multiaxial concept’) with 220 optical components and 58 degrees of freedom in cryogenic mechanisms..

These situations and designs are subject to the following parameters.

Table 1 Applied parameters on designs and technologies

	Design & Development	Manufacture & Assembly	Test	Risks (Overhead factor #)
MIDI (Old technology)	Cost and hours NA	Optics Mechanism Mounting structure	Cost NA	Cost NA
MATISSE pairwise concept MIDI technology			Warm Alignment Cold Alignment Connectivity check	Alignment error (2) Optics deterioration (3) Connectivity failure (2) Vacuum failure (3) Hardware damage (4) Hardware failure (5)
MATISSE pairwise concept New technology	Optics Clip Various Mechanisms Mounting structure			
MATISSE global multiaxial concept MIDI technology				
MATISSE global multiaxial concept New technology	Optics Clip TTM Mechanism Multi Pole Switch Mounting structure			

Note: Design and development data was not available for this MIDI. Also cost data for test and risks was not available. The MIDI data is therefore not representative to display in the cost charts.

Representing all the values of all the parameter combinations falls beyond the scope of this paper. Therefore only the results of these analyses are represented.

For all parameters cost and time was calculated, based on the formulas:

$$\begin{aligned}
 \text{Cost}_{\text{Manufacture \& Assembly}} &= \# \text{cryostat} \times \# \text{components} \times \text{cost} & (1) \\
 \text{Cost}_{\text{Design \& Development}} &= \# \text{cryostat} \times \# \text{components} \times \text{cost} & (2) \\
 \text{Cost}_{\text{Test}} &= \# \text{cryostat} \times \# \text{components} \times \# \text{iterations} \times \text{cost} & (3) \\
 \text{Cost}_{\text{Risk}} &= \# \text{cryostat} \times \# \text{iterations} \times \text{chance} \times \text{impact} \times \text{overhead factor} & (4) \\
 \text{Test Duration}_{\text{Test}} &= \# \text{cryostat} \times \# \text{components} \times \text{hours} / \text{hours per month} & (5) \\
 \text{Test Duration}_{\text{Risk}} &= \# \text{cryostat} \times \# \text{iterations} \times \text{chance} \times \text{impact} / \text{hours per month} & (6)
 \end{aligned}$$

Where:

- #cryostat = number of cryostats applicable [-]
- #components = number of components applicable [-]
- cost = cost per component or per hour [€] or [hours]
- #iterations = number of iterations [-]
- chance = chance of risk occurrence [%]
- impact = impact when a risk occurs [€] or [hours]
- overhead factor = additional factor in case of risk [-]

6.2 Results

When in the charts is referred to “Old technology”, it means the MIDI correction techniques, projected on the MATISSE designs. With “New technology” the innovative solutions as described above are projected on the designs.

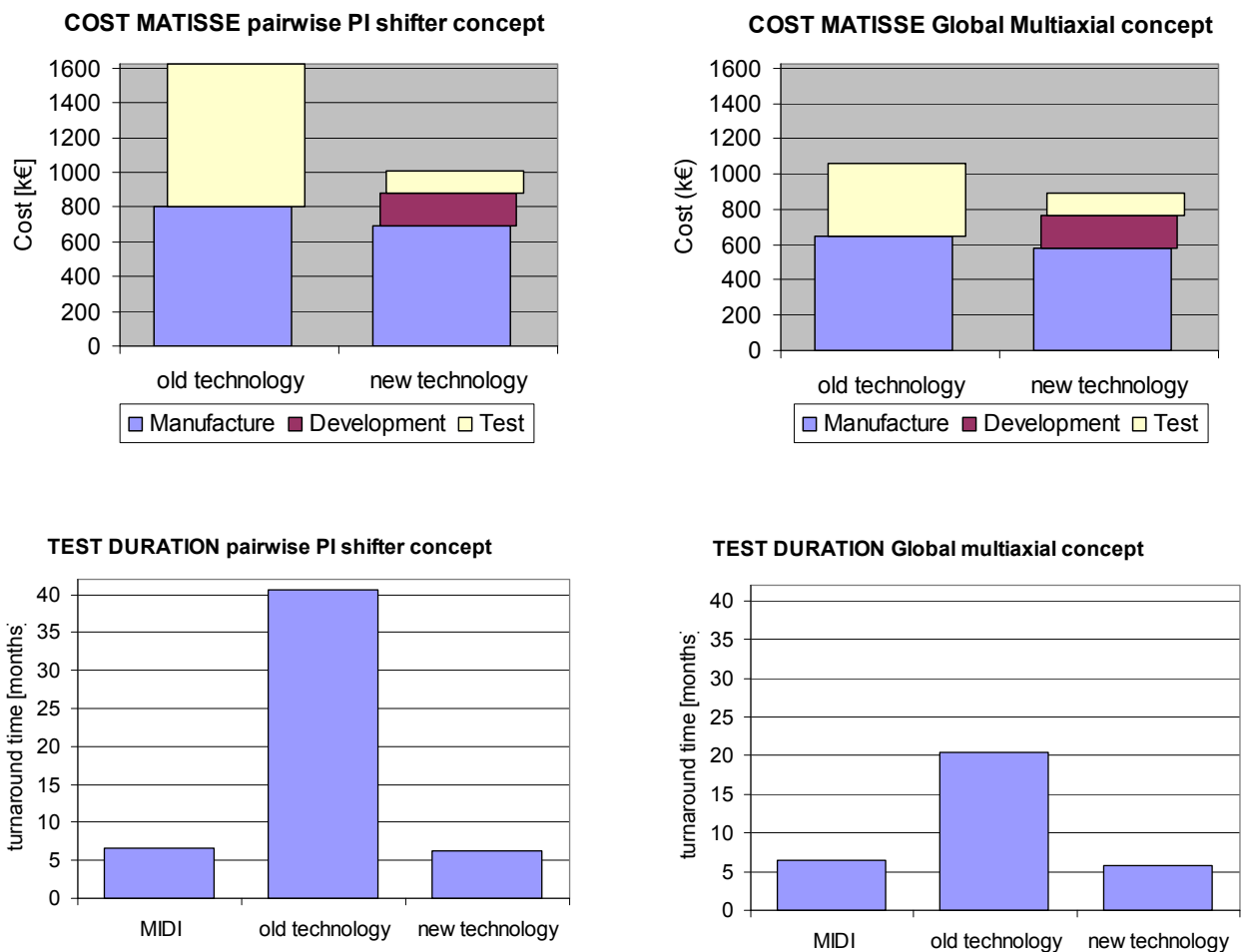


Figure 10 Charts comparing cost and hours on MAIT

Note: turnaround time is calculated assuming that 2 persons work fulltime.
Only relevant costs are shown in the plots above.

Obviously, combining the old MIDI techniques with the MATISSE Pairwise Pi shifter concept or the MATISSE Global multiaxial concept design would not only cost more, but would in particular increase project time.

7. CONCLUSION

The innovative techniques and solutions presented in the new MATISSE Global multiaxial concept design will decrease project cost and MAIT time significantly.

The solutions ease design requirements and reduce complexity of tolerance analyses and improve manufacturability.

They reduce project risks like a wrong aligned instrument, time exceeding assembly phases or broken wiring on the cryoharness.

Although no requirement, alignment or performance can always be improved during operations. For example a cold re-alignment can be performed after an earthquake or changes in the pre-optics.

Developing new techniques, design philosophies and challenging combinations of existing techniques are worth the effort.

For future projects operational active mechanism are considered. With the correct algorithm, this could lead to a single press button, automated alignment.

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