MATISSE cold optics opto-mechanical design

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ABSTRACT

MATISSE is a mid-infrared spectro-interferometer combining beams of up to four telescopes of the ESO VLTI providing phase closure and image reconstruction using interferometric spectra in the LM and N band. This paper presents the opto-mechanical design of the two cold benches containing several types of cryogenic mechanisms (shutter, Tip/Tilt) used for cryogenic alignment. Key aspects are detailed such as the highly integrated opto-mechanical approach of the design in order to guarantee component stability and accuracy specifications in the order of nanometers and arcseconds.

Keywords: MATISSE, VLTI, Mid Infrared, Interferometer, Spectrograph, cryogenic, opto-mechanics

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, MIDI[1], 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[2,3,4,5] will combine 4 telescopes simultaneously and for the very first time produce image reconstruction of the small-scale regions traced with MIDI and thus allow an investigation of these structures based on an unprecedented level of constraints. Compared to MIDI, MATISSE will have a higher spectral resolution, in the range of R ~30 – 1000, and a wider spectral coverage, L, M, and N bands, $\lambda \sim 2.8 – 13.5$ µm.

1.2 MATISSE subsystems

For an instrument like MATISSE an integrated optical, thermal and mechanical design approach at an early stage is very important in order to guarantee maximum stability and accuracy throughout the instrument. Logical subsystem division, set by either optical, mechanical or thermal requirements, will reduce complexity within the subsystems to a minimum. Subsystems can be concurrently developed and AIT risks/issues can be addressed in an early stage during instrument development. The following main subsystems are defined:

- A Warm Optics Box (WOB), providing the interface to the VLTI feeding optics and wavelength band splitting into L&M band and N band.
- Two Cold Optics Boxes (COB), one for L&M band and one for N band.
- Two Cryostats, containing one COB each.
- Two wavelength band dedicated detectors or Focal Plane Arrays (FPA), including the corresponding Electronics and Software.

This paper focuses on the COB opto-mechanical design and packaging including the relevant aspects of the cryostat design.

The design and lay-out of the MATISSE instrument and its various modules is set by the high end instrument requirements and by the available space envelope within the VLTI laboratory. The various subsystems are located as shown in Figure 1.

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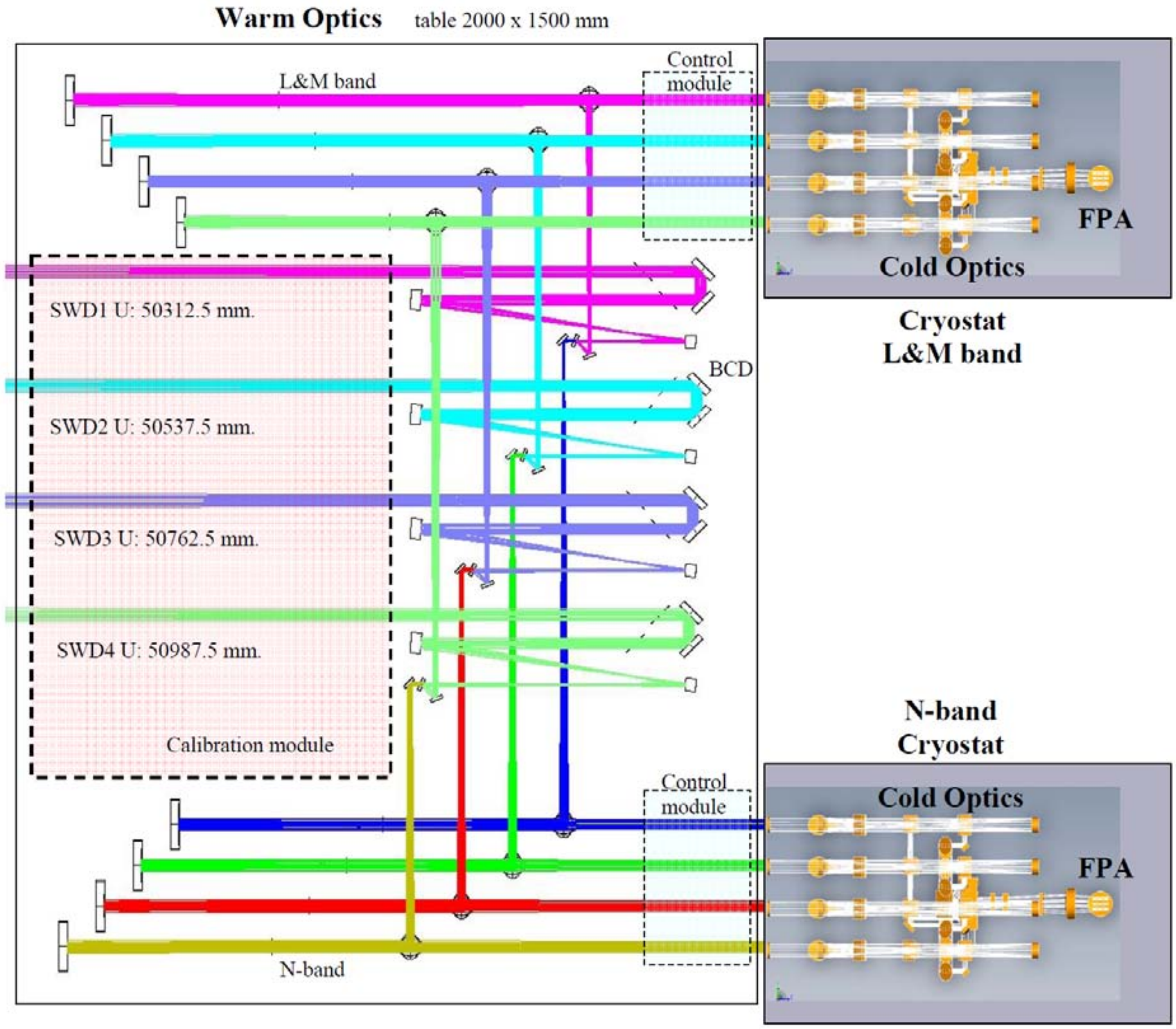


Figure 1: MATISSE instrument layout. The interface with the VLTI

1.3 MATISSE Recombination concepts

The WOB provides optical path difference correction, creation of anamorphism, beam switching, a calibration unit and wavelength separation for the two COBs input. The actual beam recombination takes place within each COB. It is very important to provide means for background subtraction, without this functionality the information is swamped by the background radiation. Several recombination concepts have been investigated (Figure 2):

- A Pair-Wise recombination system with PI-shifter (PW-PI), creating 12 interferograms on the detector (each telescope combination creates 2 interferograms: one not shifted and the other shifted in phase over half a wavelength); allowing background subtraction by comparing two (phase shifted) interferograms.
- A Pair-Wise recombination system without PI-shifter (PW), creating 6 interferograms (one for each telescope combination) and 4 photometric channels on the detector (one per telescope) for background subtraction.
- A Global Multi-Axial (GMA) recombination system, creating a single interferogram of all 4 telescopes together and 4 separate photometric channels on the detector for background subtraction.

Although the general instrument layout, subsystem division and the COB general design approach and layout are similar in all concepts, there are substantial differences. Unfortunately the PW-PI concept[4] had to be abandoned after encountering a showstopper in the stringent specification of the phase difference between the observed ZERO and PI interferograms, resulting in impossible to meet requirements on optical components and their coating and positioning.

The PW concept without PI-shifter is feasible, but the GMA concept is easier to realize and offers better performance in phase closure, with less optics and a more favourable envelope. This paper focuses on the GMA recombination concept.

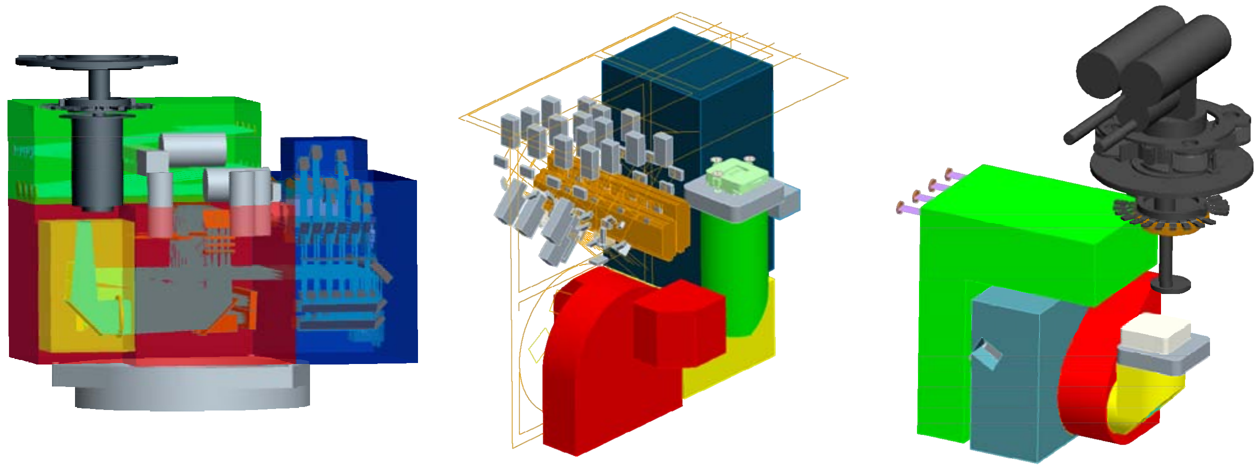


Figure 2: The three MATISSE recombination concepts side by side (at random colouring). The Pair-Wise concept with PI-shifter; PW-PI (Left), the Pair-Wise recombination without PI-shifter; PW (Centre) and the Global Multi-Axial concept; GMA (Right).

2. DESIGN APPROACH

2.1 Multidisciplinary design

To design, build and qualify a complex and expensive instrument like MATISSE, given the tight time frame and fixed resources (money as well as manpower), it is vital to follow an integrated multidisciplinary design approach as opposed to the (usual) way of disciplines working solely on their consecutive work packages.

The challenge with this design approach lies in the interdisciplinary implications, the team of individual experts should comprehend all the issues involved during the design and development process; from requirements, via optical and mechanical design to manufacturing, integration and verification. A systems (mechanical) engineer can act as lubricant/mediator between all the disciplines guarding the instrument needs. In addition several key points and design rules are applied, early in the project:

- Provide envelope for modules, structures as well as for mechanisms, coolers and also cable harnesses
- Provide sufficient envelope for accessibility, thus module and component handling
- Provide specific required orientations; e.g. the cooler
- Position of related components; cooler and detector close to each other
- Provide small overall instrument footprint
- Provide sufficient accessibility for manufacturing, integration, maintenance and upgrades
- Provide stable temperature environment:
    - Low or symmetric dT/dt; Interferometry (of 4 beams) requires a nm Optical Path Difference (OPD) stability
    - Dissipate heat sources fast by mounting at/to well cooled (non-optical) structures; mechanisms directly connected to the backbone
    - Attach modules at stable temperature levels
- Isostatic mounting is compulsory for all optics and between any temperature or CTE different interface

The advantage of an early interaction between optical, mechanical and thermal designers and manufacturers is the chance to get acquainted with the other disciplines. Do's and Don'ts can steer an instrument concept into a low risk direction. It must be said that in general one needs to learn the 'laws and limits' of the various models, which takes time, but once that's done the opto-mechanical iterations can be done quite rapidly.

2.2 No adjustment philosophy

'No adjustment philosophy' means that the optical alignment precision and thus optical performance depends strongly on the design, tolerance analysis and detailed knowledge of the material behaviour and manufacturing process. NOVA – ASTRON has proven with previous instruments; MIDI[1], VISIR[6], MIRI[7], that with this philosophy high instrument stability is achieved. Finally this strategy results in a reduction of instrument performance risks and project time.

However several issues are important regarding this 'no adjustment philosophy'. It is important to continuously track the alignment performance during the design and manufacturing phases, because in principle no corrections are possible after assembly.

In order to maintain (and gain) extensive knowledge on the achievable production tolerances, in house production capabilities for these high end parts is necessary. This generates new knowledge and possibilities to be used by (mechanical) designers to build smaller, cheaper, and better performing instruments and also more control over schedule, quality and costs, is gained. At NOVA-ASTRON instrument specifications have become more challenging over the years. The more integrated design approach has resulted in increased part complexity, size and accuracy (same manufacturing accuracy over a larger size). However during the years in house production has become an enabling technology.

Modular design

It is essential to know where optical and mechanical interfaces will be positioned. A modular design quickly reveals the position and number of critical interfaces. This allows for the construction of a 3D CAD skeleton immediately at the start of the FDR phase, even allowing interfaces to be moved or added later on. Setting up the final static mechanical tolerance chain and budget distribution is then much easier, more accurate and closer to reality as overlooking interfaces is less likely.

One of the things that can significantly delay a development process is a non fixed instrument functional specification. In that case modularity in design results in maximum flexibility as it becomes much more apparent which areas are roughly fixed in function and size. This provides the possibility for early development of critical parts like cryogenic mechanisms.

2.3 Packaging

The optical, thermal and mechanical packaging of the instrument is generally in the hands of the mechanical (systems) engineer. The optical design must be folded into the available space envelope/footprint. Normally folding the optical path does not influence the optical performance (non square folding angles do influence the polarization). The optical model is transferred to a 3D CAD environment where folds can be added and adjusted. However the transfer of the folds back into the optical design software (like ZEMAX) is a much more cumbersome operation, the typical build up of optical models does not provide much flexibility. In order to update the optical model each new fold arrangement asks for a time consuming, combined work effort of both the mechanical and the optical designer.

2.4 Accuracy specifications

All optical components in the cold optics box must be aligned such that the maximum deviation of optical beams on the detector is better than one third of a pixel = < 5 μm (pixel size = 15 μm). In the COB each beam encounters 25 optical components along an optical path of several meters. Translation of the alignment accuracy into angular tolerances per optical component results in 0.5 arcsecond per component. Together with the typical component size this corresponds to about 50 nm position tolerance on the mounting surfaces of the optics. This is not achievable in practice, especially because this requirement must be met in vacuum at the operating temperatures of 40K. In addition the instrument stability must be better than 1 nm per minute (during a 1 hour exposure) requiring additional extreme temperature stability requirements.

Optical beam alignment

In order to achieve these stringent specifications it is necessary to align each optical beam after reaching the operational temperature and then maintain this position without power. Here the successful NOVA-ASTRON no-adjustment-philosophy had to be sacrificed and specially designed piezo driven tip-tilt mirrors [8] are used to take care of the (one off) beam alignment.

By providing this (relative simple) adjustment the requirements on the rest of the optical path, thus the various optics along this path, can be relaxed. Together with the 'no adjustment philosophy' for the remaining optics, the total instrument development time and costs will be reduced.

2.5 L&M band and N band COB

The general layout and optical folding of the L&M band and N band COB are mainly identical. Special optical components like dichroics, filters, grisms and such are made dedicated per wavelength band, however this does not change the dimensions and location of the individual components and overall instrument size.

The largest size differences between the optical model of the L&M band and N band is at the location of the detector. Handling the Detector, the detector Tip/Tilt/Focus mechanism and cooling braids requires extra envelope around these components. Therefore a large separate volume with good access is needed in this area, allowing enough envelope for both camera designs.

The large similarity between the two COBs gives the possibility to concentrate on the development and qualification of only one COB. While the development of the second COB is a simple derivative from the first COB, thus reducing time and costs.

No adjustment philosophy

The L&M cryostat and N-band cryostat operate at different temperatures. On top of that they also contain other temperature regions inside the COB, along with different materials with different CTE. Therefore the non-adjustment philosophy requires a well considered strategy of resizing the optical model from operational temperature to room temperature for manufacturing at room temperature.

3. COLD OPTICS BOX

3.1 GMA development

The iterative process between optical folding (Zemax) and opto-mechanical design (Pro/Engineer) intensified greatly after freezing the functional specifications. The folding of the GMA optical model is much more straightforward than the previous (pair wise) recombination concepts. The earliest multi-axial optical models contained only few critical clearance and interference issues,these were solved in a few short iterations. Additional compression of the optical layout was achieved thus significantly reducing overall size. The GMA concept is the most flexible and "friendly" to work with. A short and effective development to this current state GMA COB is the result.

3.2 Modular set-up

The COB is divided into several opto-mechanical sub-modules. The optical functionality of the sub-modules is summarized in Table 1.

Table 1 Sub-modules and optical functionality

Backbone	No optical functionality Thermal and mechanical skeleton of the COB
Re-imager Box	Receive parallel beams from four telescopes simultaneously; Create images for each telescope to isolate the object of interest; Collimate the beams
Beam Combiner Box	Combine and shape the beams to form the desired pattern on the detector
Wheel Box	Filter and disperse the fringes in wavelength and polarization
Camera Box	Focus the dispersed patterns on the detector
Detector Box	Tip/Tilt/Focus mechanism and detector housing

This modular set-up of the COB allows maximum flexibility in design and development; if necessary (during any moment in the development process) change to one particular module, generally leaves the other modules unaffected. This setup also provides easier overall optimization, handling, tolerance distribution, resulting in risk reduction.

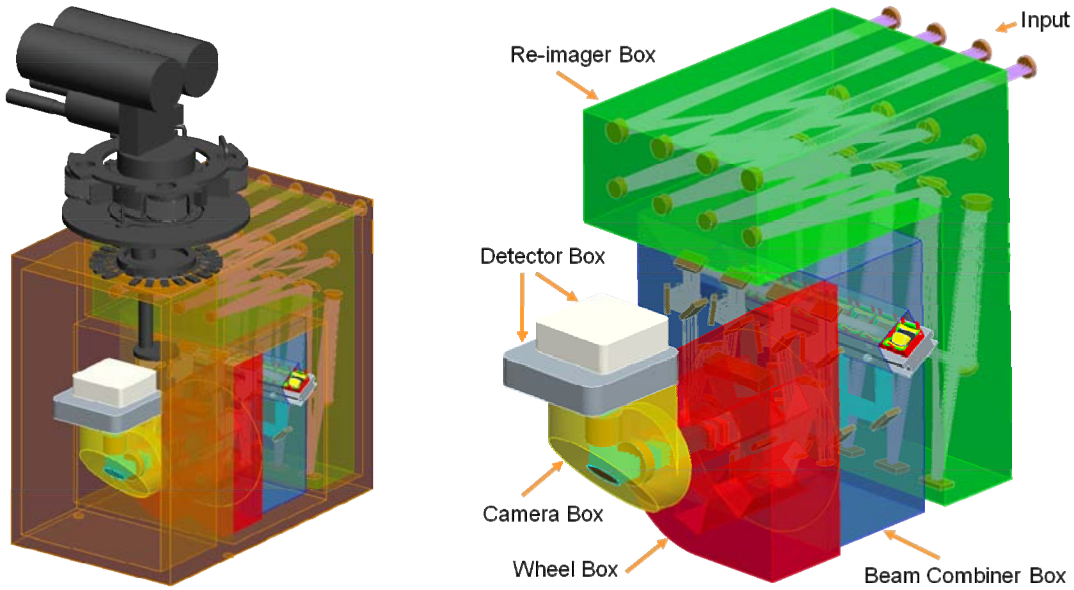


Figure 3: Modular division of the GMA COB concept, backbone and cooler not shown (right)

Backbone

The backbone will be the mechanical and thermal skeleton of the instrument. All sub-modules will be mounted to this structure and cooling will be provided through the backbone. The backbone is shaped in a symmetrical fashion in order to provide symmetrical thermal behaviour towards the sub-modules.

The backbone itself is shaped in such fashion that various manufacturing options are open. Either a single piece, a plate assembly by means of bolting or a plate assembly by means of salt dip brazing/electron beam welding. Final manufacturing of the essential interfaces will be done onto a fully assembled backbone, this way providing maximum accuracy between the different interfaces.

Re-imager box

In the GMA concept the re-imager box has a typical L-shape that protrudes into the instrument (Figure 3). The Re-imager box itself is very stiff and has a large internal thermal cross section so finding a suitable interface location will be no problem.

3.3 Observation Modes and Mechanisms

In order to keep the instrument as simple and compact as possible the various required observing modes are provided by switching between specific optical components. In order to allow this switching various mechanisms (Table 2) are foreseen, at different locations (Figure 3) within the sub-modules of the COB. All the mechanisms will be separately discussed in the cryogenic mechanisms chapter.

Table 2: COB Mechanisms

Shutters	switch between 2, 3 and 4 Telescope mode
Slit slider	switch between various slits and pinholes
Photometric slider	switch photometric channels on/off
Filter wheels	switch between various polarizer and spectral band filters (2 wheels)
Polarization wheel	switch polarization (Wollaston prism) on/off
Dispersion wheel	switch between various Prisms and Grisms

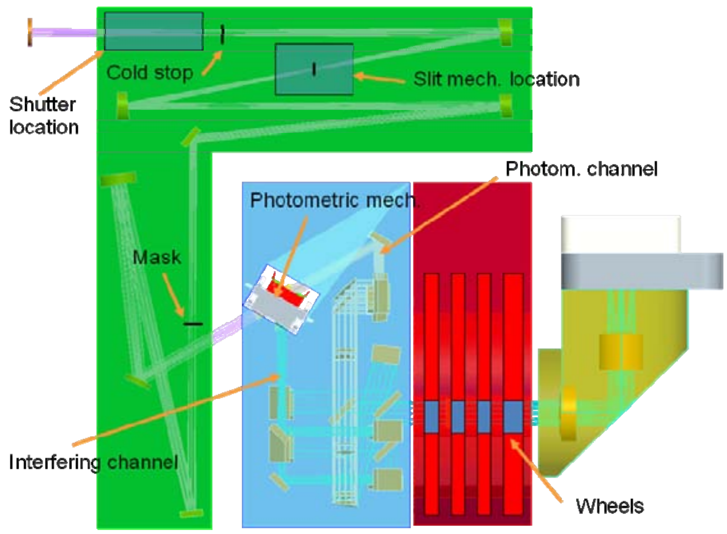


Figure 4: Location of the specific COB mechanisms

3.4 Accessibility

The various modules are designed to be easily removable. To be able to access all the critical items inside the modules during testing and for servicing, the COB optical folding and mechanical design has evolved extensively. Motors for sliding mechanisms are planned to be mounted directly to the backbone (to reduce heat load) however care must be taken not to block the handling of the modules.

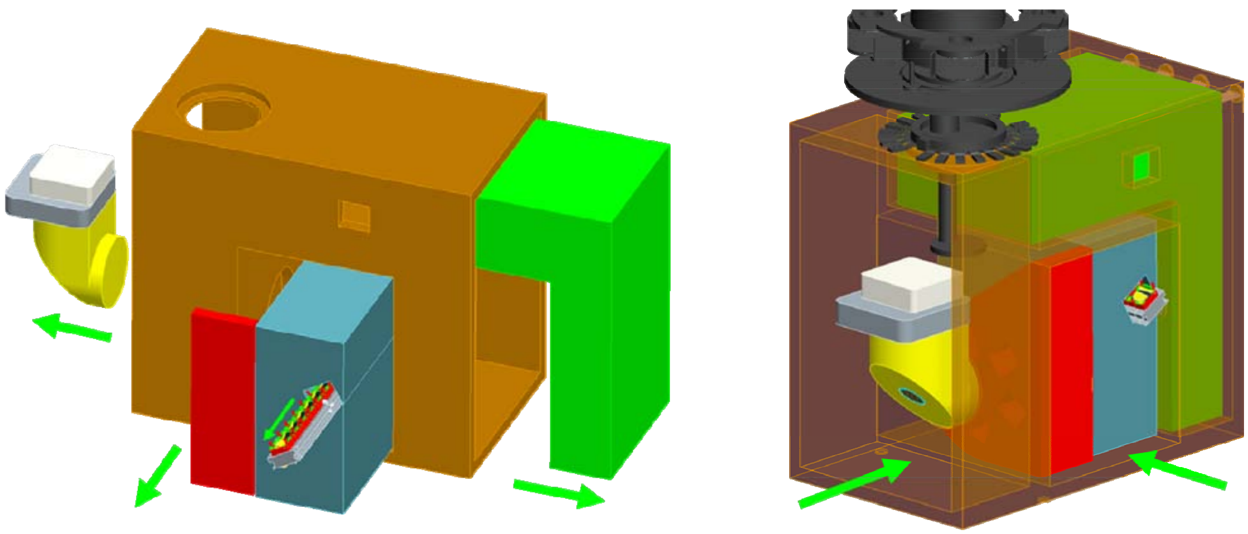
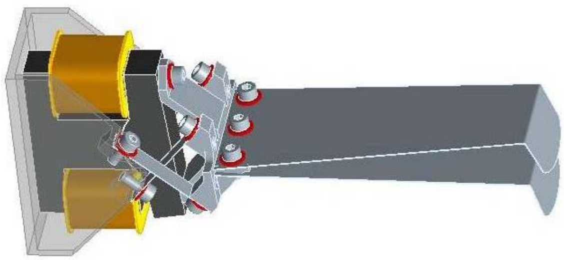


Figure 5: Left: module removal (arrows indicate slide direction). Left: Wheel Box and Beam Combiner Box will be stacked as one unit. The Re-imager Box is only removable when the whole upper part of the cryostat is removed. However, Re-imager mechanisms will be removable as a cartridge just like the Photometric mechanism. Right: the two access sides for maintenance once operational.

The carriages of the sliding mechanisms (see chapter Slider mechanism) are removable for maximum accessibility of the delicate optical elements without removing an entire sub module. This dictates a sliding direction towards one of the access directions of the COB when inside the cryostat (Figure 5). The principle applies to the Cold shutters as access to the Re-imager box is limited. The wheels are so closely located that when access is needed to the optical elements the entire module will be removed.

4. CRYOGENIC MECHANISMS

4.1 Cold Shutter



The shutter has two purposes: a light blocking function and a high speed shutter for detector remanence analysis. Providing both functionalities within one mechanism proved impossible so two shutters will be provided. The Cold Shutter is a slow and relative simple type. An off the shelf warm fast shutter is placed just before the entrance window, the side facing the cryostat is gold coated to let the detector look back into the cold environment during a remanence test.

Figure 6: Bi-stable Cryogenic Shutter Mechanism, the two blade positions are visualized

The design of the cold shutter is based on an existing design from SRON[9]. It has been adapted to the MATISSE requirements and its limited space envelope inside the re-imager box. It is a bi-stable design with crossed leaf springs acting as flexural pivots (Figure 6). The shutter switches from one position to the other by a pulse from one of the solenoids. The shutter is fixed in either position by a permanent magnet so when in position no power is required. The design of the moving is balanced so switching of the shutter is not affected by its mounting orientation. For the given footprint and with the current setup an angular movement of 8 degrees between positions suffices

4.2 Slider mechanism

The slider mechanism uses a specific guiding philosophy, previously used in MIDI[1]. By mounting a carriage onto 5 kinematical located ball bearings it is constrained in 5 Degrees of Freedom (DoF) 3 rotations and 2 translations. Located opposite these ball bearings are 5 additional, but spring loaded ball bearings, providing a holding force to the carriage. By proper orientation of these ball bearings they will act as track rollers and provide 1 translation DoF and thus a sliding motion of the carriage (Figure 7). This motion is actuated by a cryogenic compatible motor.

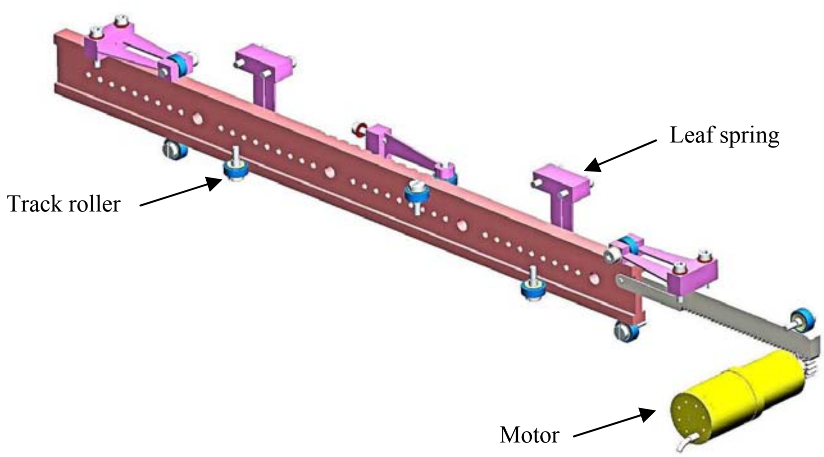


Figure 7: Slit slider mechanisms showing the general mechanism principle; 5 accurately positioned ball bearings that act as track rollers with 5 additional spring loaded bearings positioned opposite these 5 track rollers and a motor attached to the carriage to allow a sliding motion.

Slit Slider

The slit slider mechanism follows the basic slider mechanism principle as explained before. For accurate positioning of the slider the principle of positioning by accurately located V shaped indents is used; a small pre loaded ball bearing is pushed into the V shaped indent.

The motor pushes (or pulls) the slider from one indent to another, thus each time selecting a different pinhole/slit. Deliberate play between the motor and the slider ensures accurate positioning by the indent rather than by the motor position.

The available instrument footprint for the GMA concept sets the space envelope overall COB width at 400 mm. Unfortunately the shortest possible slider width of 430 mm, set by the number of slits and pinholes, requires a minimum COB width of 440 mm. Although this considerably smaller than the initial 600 mm for the PW-PI concept, a different slit mechanism concept has to be found when this overall COB width is unacceptable.

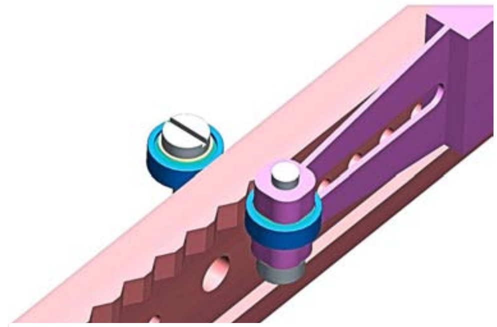


Figure 8: Slit slider indent positioning principle

Photometric slider

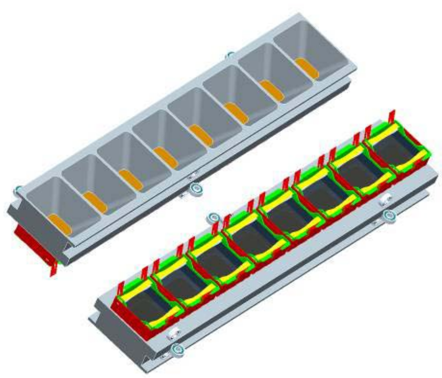


Figure 9: Photometric slider mechanism

In order to provide interferometry without photon loss (by the photometric channels) the beam splitters can be replaced by a reflecting mirror. The beam splitters and mirrors are alternately positioned on the carriage. Again the photometric slider follows the main slider principles. Only two positions are needed and the flat beams splitters and mirrors do not require accurate positioning along the motion direction of the slider, so no indents (as in the slit slider) are required and reference switches are provided for position control.

The most accurate ball bearings have an inevitable wobble of around 1 µm, resulting in a tilt of the whole carriage after repositioning. This tilt results in a position error of the complete interferogram on the detector. The track rollers are positioned in such fashion that the tilt is largest in the (less sensitive) spatial direction but smallest in the (most sensitive) spectral direction, worst case tip/tilt error of a beam splitter/mirror: rY = 0.041 mrad and rZ = 8.3 µrad, see Table 3 for position errors.

Table 3: position error caused by slider tilts due to bearing wobble

Rotation axis slider	Direction on detector	Displacement [µm]	Displacement, [pixel]	Requirement [pixel]	Goal [pixel]
rY (global)	Spectral	0.021	7.1e-4	3	0.3
	Spatial	100	3.3	10	3
rX (global)	Spectral	3.4	1.1e-1	3	0.3
	Spatial	0.003	1.0e-4	10	3

4.3 Tip-Tilt Mirror

The Piezo driven Tip-Tilt Mirror (TTM)[8] consists of a small square mirror (33 x 33 mm) that is manipulated with microrad resolution within a range of several millirads (Figure 10). Specially designed for operation in cryogenic environment (vacuum, 30 - 100K) full functionality is also needed in ambient environment. Once aligned the mechanism shall maintain its position powerless during operation.

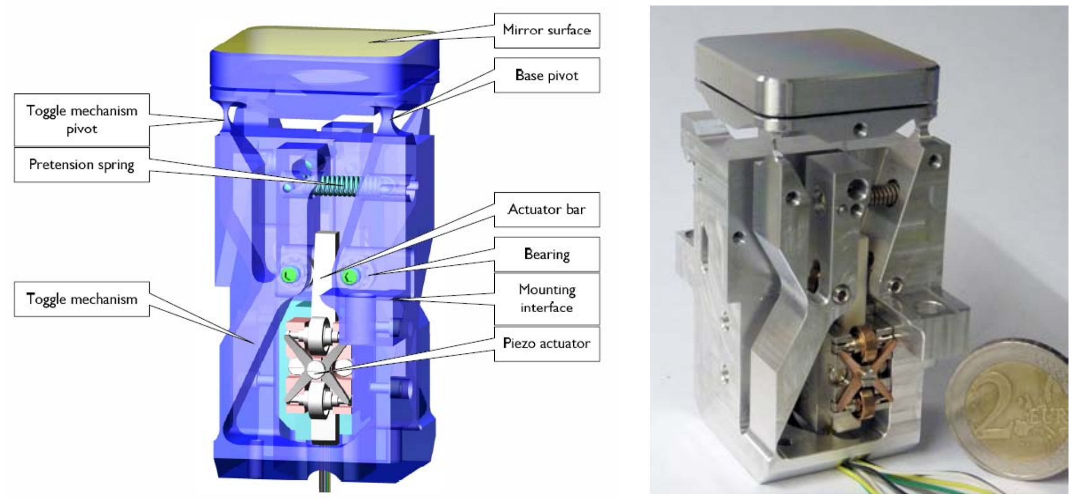


Figure 10 Tip-Tilt Mechanism including piezo motors

The impact of this element and other elements like the mirror clip and the detector tip-tilt-focus mechanism on the Manufacture, Assembly, Integration and Test plan (MAIT) is extensively discussed in this paper[10].

4.4 Mirror Clip

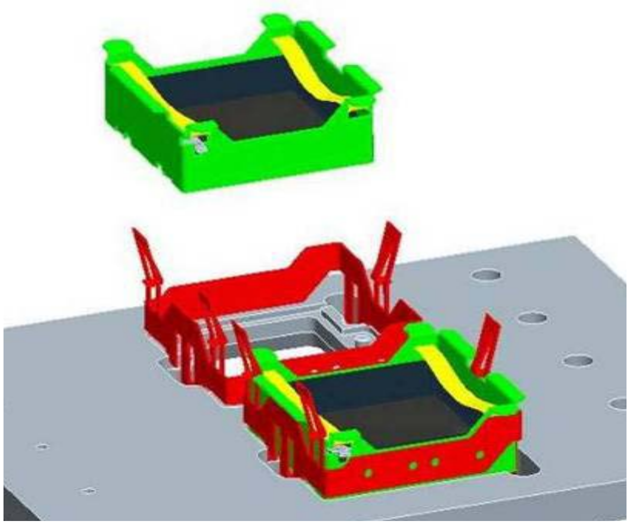


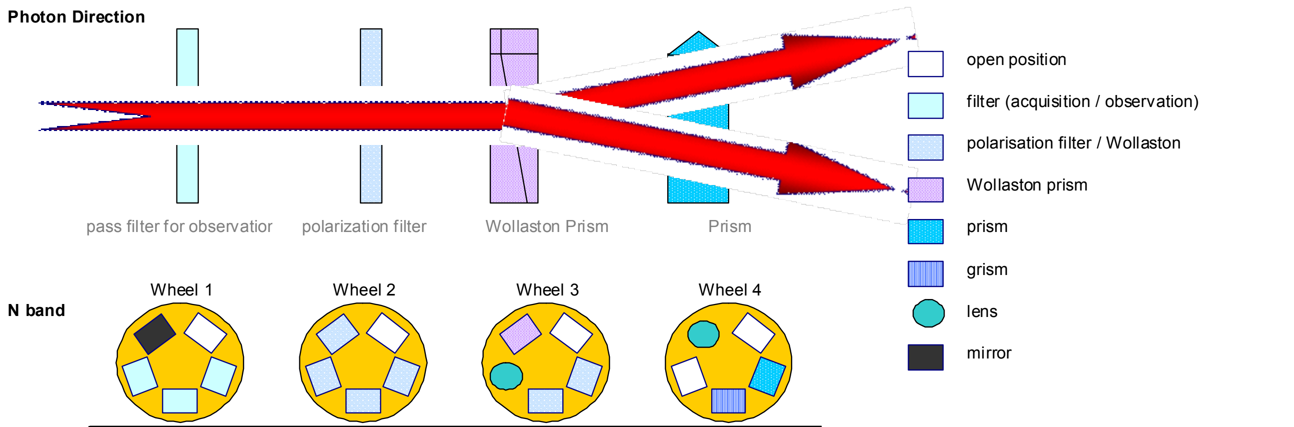
Figure 11: Mirror clip design, in the air the optical element assembled into the mirror cell by means of leaf springs, at the front in fully assembled state

Although not an active mechanism, the mirror clip is an essential COB development. The main purpose of the mirror clip is to provide isostatic mounting of flat optical components (beams splitter/flat mirror) and allow integration on the optical bench single handed, without the use of any tools. The basic idea behind the mirror clip is to reduce the number of parts, risks and time spent on assembly for the large number of small optical elements.

The design is a two stage assembly. The optical element is mounted in a mirror cell. Leaf springs provide a holding force to lock the optical element in position within the mirror clip but also when fully assembled with the cage. The full assembly can be clipped into the cage which is earlier mounted onto the structure. A fully assembled mirror cell can be safely stored for later handling. On the cage special release levers are provided to allow single handed dismounting of the mirror cell and the cage.

4.5 Wheels

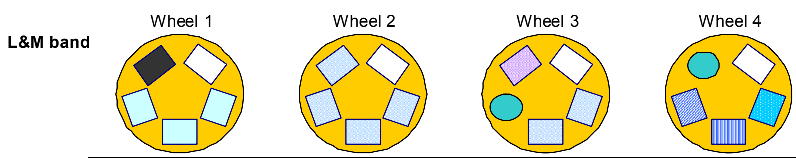
Up to four optical elements need to be inserted simultaneously in the optical path. This is the reason for implementing four different wheels in the wheel box. The first wheel mainly contains band pass filters, the second wheel polarization calibration filters, the third wheel a Wollaston prism and other polarization filters and the fourth wheel contains dispersion optics. Several open positions are filled with elements to aid alignment and calibration of the instrument. The split in the Wollaston prism is orthogonal to the spectral separation by the grism. An overview of the optical elements in the wheels is provided in Figure 12



	Wheel 1	Wheel 2	Wheel 3	Wheel 4
1	open position	open position	open position	open position
2	spectral filter for calibration	1/2 lambda 0°	parallel polarization	prism (low resolution)
3	N+ filter for target acquisition	1/2 lambda 22.5°	perpendicular polarization	grism (high resolution)
4	N- filter for target acquisition	1/2 lambda 45°	lens for flat field	
5	mirror for detector dark	1/2 lambda 67.5°	Wollaston prism	lens for pupil visualization

on fixed optics (camera lens):

N band pass filter for observation (8-13um)



	Wheel 1	Wheel 2	Wheel 3	Wheel 4
1	open position	open position	open position	open position
2	L band pass filter for observation (-4.0)	1/2 lambda 0°	parallel polarization	prism (low resolution)
3	L- band pass filter for observation (-3.4um)	1/2 lambda 22.5°	perpendicular polarization	grism1 (medium resolution)
4	spectral filter for calibration	1/2 lambda 45°	lens for flat field	grims 2 (high resolution)
5	mirror for detector dark	1/2 lambda 67.5°	Wollaston prism	lens for pupil visualization

on fixed optics (camera lens):

LM band pass filter for observation (2.8-5.5)

Figure 12: The wheel box contains 4 wheels with 5 optical components each.

4.6 Detector Tip-Tilt Focus

A special tip/tilt/focus mechanism will be used to (infrequently) accurately position the FPA in the best focus position and orientation. Manually adjusting the focus is a painstaking, time consuming operation, because a full warm-up cool-down cycle is needed to make an adjustment. Therefore a simple piezo driven unit is developed at NOVA-ASTRON[11].

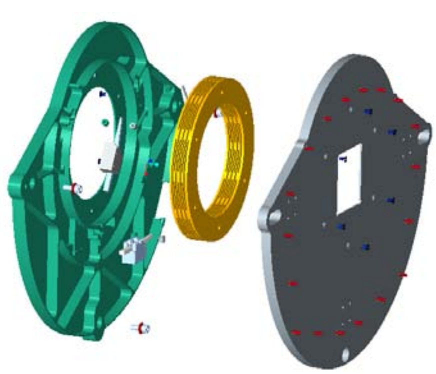


Figure 13: NOVA-ASTRON piezo driven tip/tilt/focus unit

5. CONCLUSIONS

The development of the optical folding and global layout is dictated by the need for a smaller instrument footprint and a lower number of optical elements. From an opto-mechanical standpoint the Global Multi Axial design results in the smallest and simplest concept.

The total size of a single global multi axial cold optics box is: 685x440x630 = 190 litre (LxWxH) while containing a total number of about 220 optical components; 20 optical components are needed per input telescope and in addition about 30 optical components are needed in the common path of each cryostat (most of these optical components are located on the wheels). This includes the optical elements necessary for the photometric channels. Two Anamorphic mirrors are needed to create a pattern on the detector that is sufficiently large to distinguish the six different baseline signals in the interferogram. There are 16 other powered mirrors per cryostat, 4 beam splitters (all of a single type only), 61 all small folding flats (of which 8 are TTMs) and two medium diameter camera lenses.

The next step is to incorporate all mirrors (clips) and mechanisms into GMA design to find any remaining interference issues. So far the design looks promising. Future development of the COB will focus on the exact interface locations of the modules with respect to the backbone based on accessibility, manufacturability, testability, opto-mechanical tolerances and thermal constraints.

REFERENCES

[1] Leinert, C., et al., “Ten-micron instrument MIDI: getting ready for observations on the VLTI,” Proc. SPIE 4838, 893 (2003)

[2] Lopez, B., et al., “MATISSE: perspective of imaging in the mid-infrared at the VLTI,” Proc. SPIE 7734, 34, (2010)

[3] Lagarde, S., et al., “MATISSE: Concept Analysis,” Proc. SPIE 7013, 701332 (2008)

[4] Petrov, R., et al., “The potential performance of the mid-infrared second-generation VLTI instrument MATISSE,” Proc. SPIE 7734, 35 (2010)

[5] Robbe-Dubois, S., et al., “Fresnel diffraction in an interferometer: application to MATISSE,” Proc. SPIE 7734, 143 (2010)

[6] Lagage, P.O., et al., “Final design of VISIR: the mid-infrared imager and spectrometer for the VLT,” Proc. SPIE 4008, 1120-1131 (2003).

[7] Wright, G. S., et al., “The JWST MIRI instrument concept,” Proc. SPIE 5487, 653-663, (2004).

[8] Janssen, H., et al., “Design and prototype performance of an innovative cryogenic tip-tilt mirror,” Proc. SPIE 7739, 83 (2010)

[9] Wildeman, K., et al., “Shutter for the Short Wavelength Spectrometer in ISO,” Cryogenics, Volume 29, Issue 5, Space Cryogenics Workshop May 1989, 546-549 (1989)

[10] Elswijk, E., et al., “The innovative MAIT plan for the MATISSE cold optics, comprising an unprecedented 220 cryogenic optical components,” Proc. SPIE 7739, 167 (2010)

[11] Pragt, J., et al., “Piezo-driven adjustment of a cryogenic detector,” Proc. SPIE 7018, 70184N (2008).

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