Realization of the MIDI cold optics.

A.W. Glazenborg-Kluttig[a*], F. Przygodda[b**], H. Hanenburg[a], S. Morel[c], J. W. Pel[d]
[a] ASTRON, Dwingeloo, The Netherlands; [b] MPIA, Heidelberg, Germany; [c] ESO, Garching, Germany; [d] RUG, Groningen, The Netherlands;

ABSTRACT

MIDI is the Mid-Infrared interferometer for ESO's VLTI (Very Large Telescope Interferometer), which has been developed by a German-Dutch-French consortium [MPIA Heidelberg Germany, NOVA/ASTRON Dwingeloo Netherlands, Observatoire de Meudon France]. The initial aim of MIDI is to combine the beams from 2 telescopes in the 10micron N-band with a spatial resolution of up to 10milli-arcseconds and a maximum spectral resolution of 230. Modulation of the optical path difference can be done using piezo-driven mirrors at room temperature, but beam combination and detection of the interferometric signal has to be done at cryogenic temperatures due to the 'thermal' wavelength domain. The MIDI cold bench is therefore mounted inside a cryostat, cooled by means of a closed cycle cooler to about 40K for the cold optics and 8K for the detector.

The design of the cold optics has been kept as simple as possible, creating challenges such as preserving alignment from 295K to 40K and accessibility. This poster describes the realization of the cold optics, the alignment and test strategies and laboratory results.

Keywords: Interferometry, infrared, VLTI, cryogenic, MIDI, VLT

1. INTRODUCTION

1.1 Optical layout

The aim of MIDI is to combine interferometrically the parallel beams of two different VLT telescopes, which can be either 8.2m Unit Telescopes (UTs) or 1.8m Auxiliary Telescopes (ATs). The wavelength range of MIDI is centered on 10microns (N-band). In a later phase this could be extended to the 20micron region (Q-band).

The layout of the MIDI cold optics on top of the cold bench is relatively simple and consists of four sections. From the cryostat entrance window to the detector (a Raytheon 240x320 Si:As BIB array) light passes the 're-imager', the beam-combiner, the dispersion/filtering section and the camera optics. Up to the beam combiner, the system is purely reflective and all optical elements are in pairs, one set for each beam. After the beam combiner, all beams pass through the same refractive elements. The optical configuration is shown in Figure 1 and a more detailed description of the MIDI optical design is given in Glazenborg [1].

The two MIDI input beams enter the cryostat with 18mm beam diameter, separated by 30mm to allow for baffling. In the re-imager section, both beams first pass an undersized cold pupil stop. The off-axis paraboloids M1, mounted on a focusing stage, then create an intermediate focal plane where pinholes or slits (a fiber will be a later addition) can be selected for spatial filtering. A second pair of off-axis paraboloids M2 re-collimates the beams to a diameter of 10mm. A folding flat reflects these beams upward into the beam combiner.

In the beam combiner (made of ZnSe) both beams are coherently combined to produce the interferometric information. A fraction of the light of the input beams can bypass the beam combiner and be used for photometric monitoring.

* glazenborg@astron.nl; phone +31 521 595 100; fax +31 521 597 332; http://www.astron.nl; ASTRON, PO Box 2, NL7990AA Dwingeloo, The Netherlands.
** przygodd@mpia-hd.mpg.de; +49 6221 528 215; fax +49 6221 528 246; http://www.mpia-hd.mpg.de/MIDI/; MPIA, Königstuhl 17, D69117 Heidelberg, Germany.

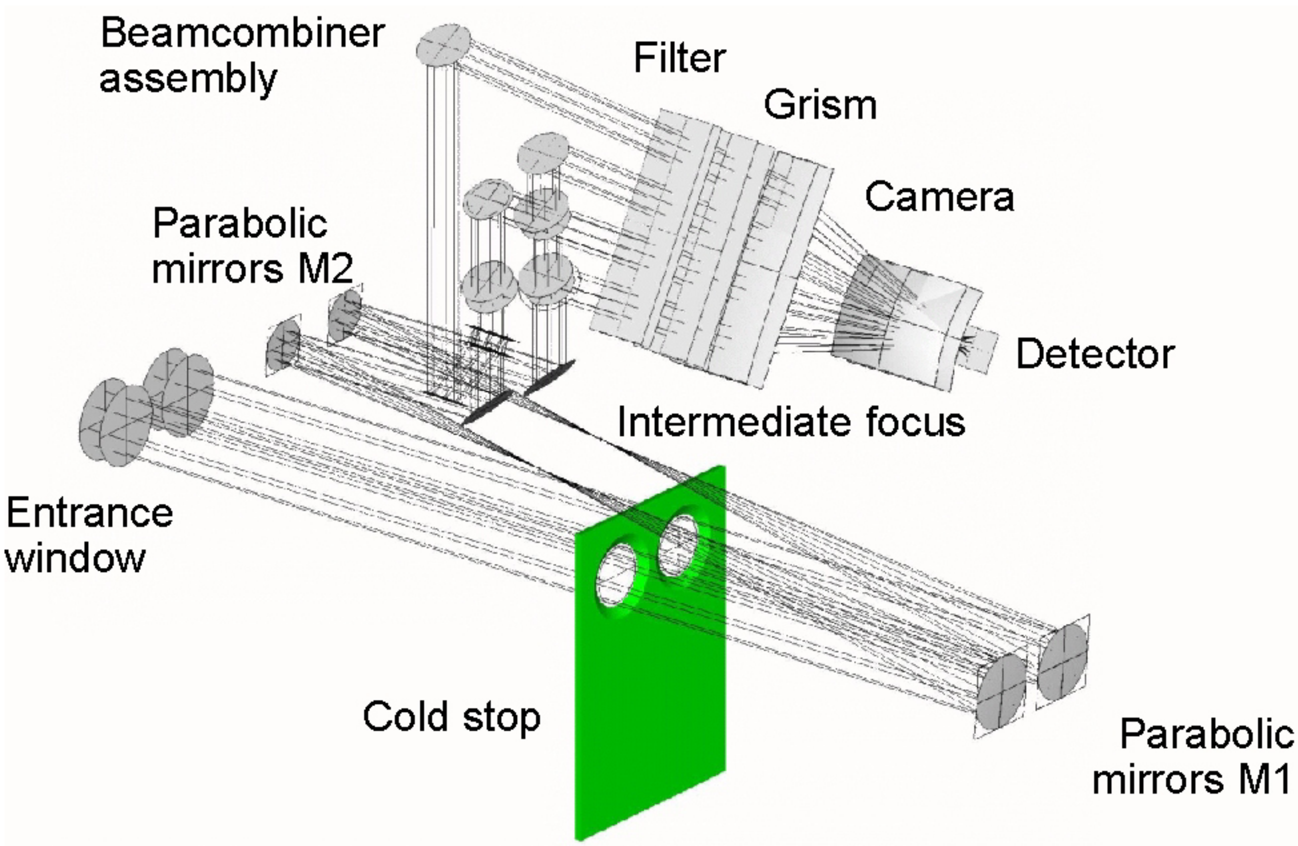

Figure 1: The optical path of the MIDI cold bench.

After the beam combiner there can be up to four beams: two interferometric channels and two photometric reference channels. Via the filter wheel (choice of 10 passband filters), the dispersion element (grism or prism; spectral resolution ~230 or ~30) and the camera optics, these beams are imaged as four parallel spectra on the detector, with the dispersion in the horizontal direction. The camera optics are mounted on a slider mechanism that allows a choice between the main spectroscopic camera (with toroidal optics optimized for different pixel matching in the dispersion and field directions), a spherical camera optimized for the imaging mode (without grism/prism) and a simple pupil imaging camera for diagnostic purposes. Figure 2 shows a photograph of the cold bench with all the subsystems mounted. The only elements not mounted are the detector, grism and prism.

The wavelength range of MIDI is the 'thermal infrared' and therefore the entire cold bench has to be cooled down to about 40K and the detector down to 8K. The whole instrument is mounted in an isolated vacuum chamber of about 57x60x80cm (lxwxh) size.

1.2 Subsystems

The main subsystems of the cryogenic MIDI optics are:

1. *Shutter* – the shutter can independently switch on and off the incoming light beams
2. *Cold-stop* – defines the pupil of the incoming beams and blocks stray light
3. *Parabolic mirrors M1* with focusing mechanism – re-image focal plane; adjustment of the intermediate focus
4. *Intermediate focus* – a range of pinholes and slits are available for spatial filtering in the focal plane; position for spatial filtering by a fiber is foreseen.
5. *Parabolic mirrors M2* – recollimate the beams to a diameter of 10mm.

6. *Fixed folding flat M3* – directs the beams into the beam combiner
7. *Beam Combiner* – splits and recombines the 2 incoming beams to produce 2 interferometric beams and also allows for some light to be split off to form 2 photometric reference beams, one for each incoming beam
8. *Filters* – ten filter positions are available
9. *Dispersion* – a full N-band grism and a low resolution prism are available initially
10. *Camera* – 3 cameras are included, one for spectroscopy, one for imaging and a pupil imaging test camera
11. *Detector* – detects the incoming signals in the two interferometric beams and the two photometric reference beams
12. *Autocollimation* – a number of autocollimation flats for alignment checks are foreseen in various places on the cold bench
13. *Base plate* – an aluminum optical table (~42x57cm) supports the entire cryogenic optics

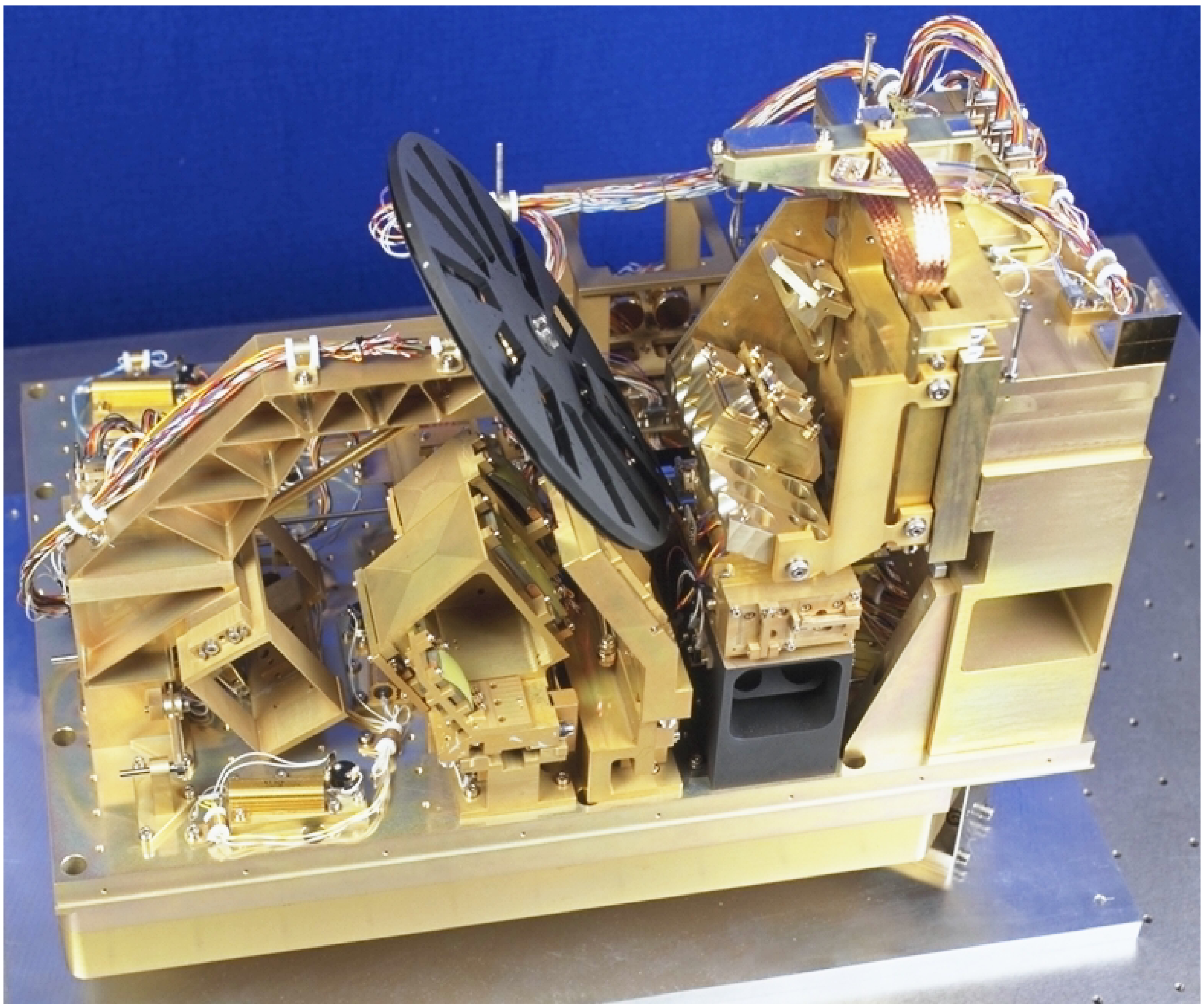

Figure 2: Photograph of the cold bench.

2. MECHANICAL DESIGN AND MANUFACTURE

Figure 2 shows an overview of the MIDI Cold Optics. All mechanical parts are made of Aluminum alloy Al 6061-T651 as this results in good heat distribution and low mass. The golden appearance is due to the protective alodine coating and the black surfaces have been anodized.

The instrument is very crowded and has eight moving mechanisms. Six of these are located very close to each other, which was one of the main problems in designing the mechanics. The mechanisms move the optical elements in and out of the light path as required. The movements have to be very accurate. For example, the pinhole slider needs a repeatability accuracy of 10microns over a travel distance of 25mm. Even worse is that the whole instrument is cooled down to 40K and is in vacuum. The result is that at working temperature the instrument is 2.5mm smaller than at room temperature.

The motors that drive the mechanisms are outside the cryostat and are connected to the mechanisms by axles and feedthroughs. The play in the drive axles needed to compensate for the shrink makes it impossible to assure the required position accuracy. The solution is not to rely on the motor to obtain the accuracy under these circumstances. The position accuracy is instead built into the mechanism itself. Each mechanism has a spring-loaded wheel that snaps into a V-groove at the desired position. As these V-grooves are part of the mechanism, they have the same temperature and so the accuracy is assured.

The mechanical design of the MIDI cold optics was governed by the following criteria: -

a) Monolithic structures. It is well known that mounting techniques like welding or brazing introduce stresses in materials. Bolted connections can result in slip-stick effects and in poor thermal connections. To prevent such sources of mechanical instability and improve thermal behaviour, structures are manufactured where possible from one monolithic piece.

b) Homogeneity. When different materials are used, differential thermal shrink will occur. In order to minimize thermal effects on the optical alignment of the instrument, all structures and reflective optical elements will be made of one material: aluminum alloy Al 6061-T651. The total thermal shrinkage from 300 to 40K is 0.42% for this material. This homogeneous design ensures homologous shrinking, which means that the cold bench internal optical alignment (apart from focus effects in the cameras) is maintained between room temperature and 40K.

c) Isostatic mountings. Hyperstatic mountings can transmit stresses between structures. The only correct way to avoid this is by applying isostatic mountings, which constrain each of the six degrees of freedom of a component only once. This means that no stiffness can be passed on from one structure to another and thus that every unit should be stiff in itself. There are standard mechanical design methods to achieve this. Isostatic mountings are particularly useful in a cryogenic instrument like MIDI to avoid problems with differential thermal shrinkage. Stress-free mountings are also very important for positioning of the optical elements. Mechanical stress cannot only cause displacements but it can deform the optical surfaces, resulting in optical quality loss or damage. The isostatic design strategy is therefore driven by mechanical, thermal and optical considerations and it is applied throughout the optomechanics of the MIDI cold bench.

d) Mirror mountings. For the reflective optics special mountings are applied, making use of the experience gained in the development of VISIR, the VLT mid-infrared imager/spectrograph. For the attachment of mirrors with different sizes and weights, different versions of the isostatic 'Three-Point' or 'Wineglass Foot' mountings are used. The Three-Point-Mounting consists of three stress-released lugs at the mirror edge. The Wineglass Foot Mounting, named after its shape, is a special kind of single point mounting that was also modeled and tested extensively for VISIR by ASTRON in Dwingeloo. In MIDI it is used for the parabolic mirrors. This kind of stress-free mounting is attractive because of its simplicity and low weight.

e) Mounting of refractive elements. Special attention has been given to the mounting of the refractive optical elements: grisms (KRS5), prism (NaCl/Ge), beam combiner plates (ZnSe), filters and lenses (Ge). Thermal expansion differences are particularly dangerous here and KRS5 is known to be very sensitive to stress. To avoid stress problems, the isostatic mountings of these optical elements include spring-loaded contact points.

f) Adjustments. Since the cold optics are mounted inside a vacuum enclosure, it is important to keep the number of mechanisms and adjustments to a minimum. Using the optical tolerance analysis, we have verified that for nearly all cold bench components optical and mechanical manufacturing precision is sufficient to obtain the required positioning accuracy without provision for fine-adjustments. There are three exceptions: parabolic mirrors M1, parabolic mirrors M2 and the detector. To allow on-line adjustment, the M1 paraboloids and the detector are mounted on focusing stages with external motor drives. The parabolic mirrors M2 have fine-adjustments for alignment during assembly of the instrument.

g) Lightweighting. The instrument will go through many cool-down/warm-up cycles during its lifetime. To decrease cooling and warming time the total mass of the instrument is minimized. Weight reduction is also desirable from the point of view of structural flexures. Material choice and light weighting can accomplish this weight reduction. The 6061-aluminum alloy is a low-mass material with a good stiffness/weight ratio. With light weighting, this ratio is optimized. Furthermore, from extensive testing of 6061 mirrors for the VISIR instrument, we know that this alloy is suitable for CNC diamond-cutting of light-weighted mirrors that are accurate and stable at cryogenic temperatures.

h) Uniformity. Wherever possible, the same construction principles are used for the different mechanisms. The optics have, as far as possible, similar mountings and all mechanisms have the same motor drives. This way an orderly design is created, and research and development effort is minimized. Easy maintenance and minimization of spare parts is another advantage of a uniform design.

i) Instrument lifetime. The expected lifetime of MIDI will cover about 10000 observing hours (thousand 10-hour nights). The most frequently used functions (cold shutter and filter wheel) are expected to make ~10^5 movements over this lifetime. This means that instrument wear is not a major design issue.

j) Material treatment. After manufacturing, all mirror blanks and structural cold bench components are stress-released by thermal treatment. Mirror surfaces are coated by vacuum-deposited gold coating on a Ti bonding layer. Refractive optical elements received multilayer filter-, beamsplitter- or anti-reflection coatings. Baffles are black-anodized and an 'alodine' protective chromate layer is given to all aluminum structure surfaces.

k) Stability. The MIDI cold optics are mounted inside a cryostat on a fixed optical table in the temperature-stabilized VLTI beam combination room. Therefore, instability due to temperature variations or orientation-dependent flexure is not an issue. However, since MIDI is an interferometer, it is very sensitive to vibrations. Special attention is therefore given to elimination of vibrations from the cooling system. For this reason the Sumitomo closed-cycle cooler, which has been selected for its low vibration noise, is mounted on a separate support, mechanically de-coupled from the MIDI cold bench.

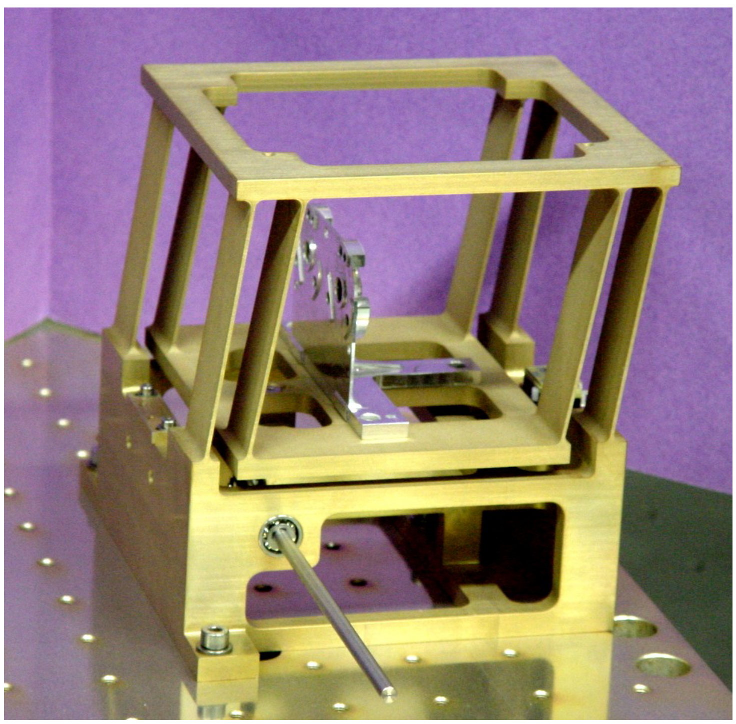

Figure 3: M1 focusing unit without mirrors.

A mechanism of special interest is the focus mechanism of M1 mirrors. These parabolic mirrors (not shown) focus the incoming beams into the pinholes and are mounted on the focus mechanism. The focus mechanism is a two stage leafspring construction. The two stages reduce the non-linear motion and the height of the mechanism. The total focusing travel is 5mm. The rotation of the drive axle is converted to linear movement by an excenter, which cannot be seen. The moving force is applied to the middle of the mirror platform in order to exclude tilt deviations. To ensure mechanical and thermal stability the focus mechanism is monolithic. It is made using conventional machining and electro-discharge machining (EDM).

Figure 4: M2 mirrors mounted on a leafspring mounting block.

The above 2 mirrors are off-axis paraboloids of a 'Wineglass Foot' design. They are the M2 mirrors, which recollimate the beams to a diameter of 10mm. The mirror surfaces measure 14mm in diameter and are gold coated. Three slits are visible in the foot of each mirror. These stop any stress induced by the fixing screws from being transmitted into the mirror surface The mounting block is made from one piece of aluminum, into which 2 leafsprings have been cut using EDM. The leafsprings allow one mirror to move 'up/down' and the other to move 'left/right'. This gives a very fine adjustment on the position of these mirrors. The mounting block has been alodined in order to protect the aluminum surface and hence appears to be gold in colour.

3. ALIGNMENT

The alignment of the MIDI cold optics must be done at room temperature as the design of the cold bench is such that no adjustments are possible when the cryostat has been closed. The final result of the alignment however is not known until the cryostat has been closed and the instrument is operating at cryogenic temperatures.

For the majority of the optical elements, the alignment can be done using optical light. The alignment is done step-by-step mainly following the optical path of the input beams. A very high accuracy is needed, for example the focus of the beams from the M1 mirrors must lie at the center of the smallest, 70micron, pinholes. As the focal length is 180mm, the tilt of these mirrors must be adjusted to within a range of less than 10arcsec. This can be achieved by 'polishing' the mounting surface of the mirror.

The first item to be placed on the base plate, is the pinhole unit (intermediate focus), this then becomes one of the references for the alignment procedure. A second reference is an external reference flat, which can be attached to the front of the base plate. Next the M1 unit is placed on the base plate and the mirrors aligned to the pinhole unit. This is followed by the M2s, which are mounted on the shutter unit. These units are placed on the base plate and then the M2 mirrors aligned. M3 is attached to this unit and does not require aligning. Next the beam combiner unit is placed on the base plate and the M6 mirrors aligned so that overlap in both the image and pupil planes is achieved. A check on the positions of the exiting beams must then be done to ensure that the beams will hit the dispersive elements, camera and detector in the correct places. These items cannot be checked using visible light. Of the 2 photometric beams, only one can be adjusted by moving mirror M5. The other is permanently fixed.

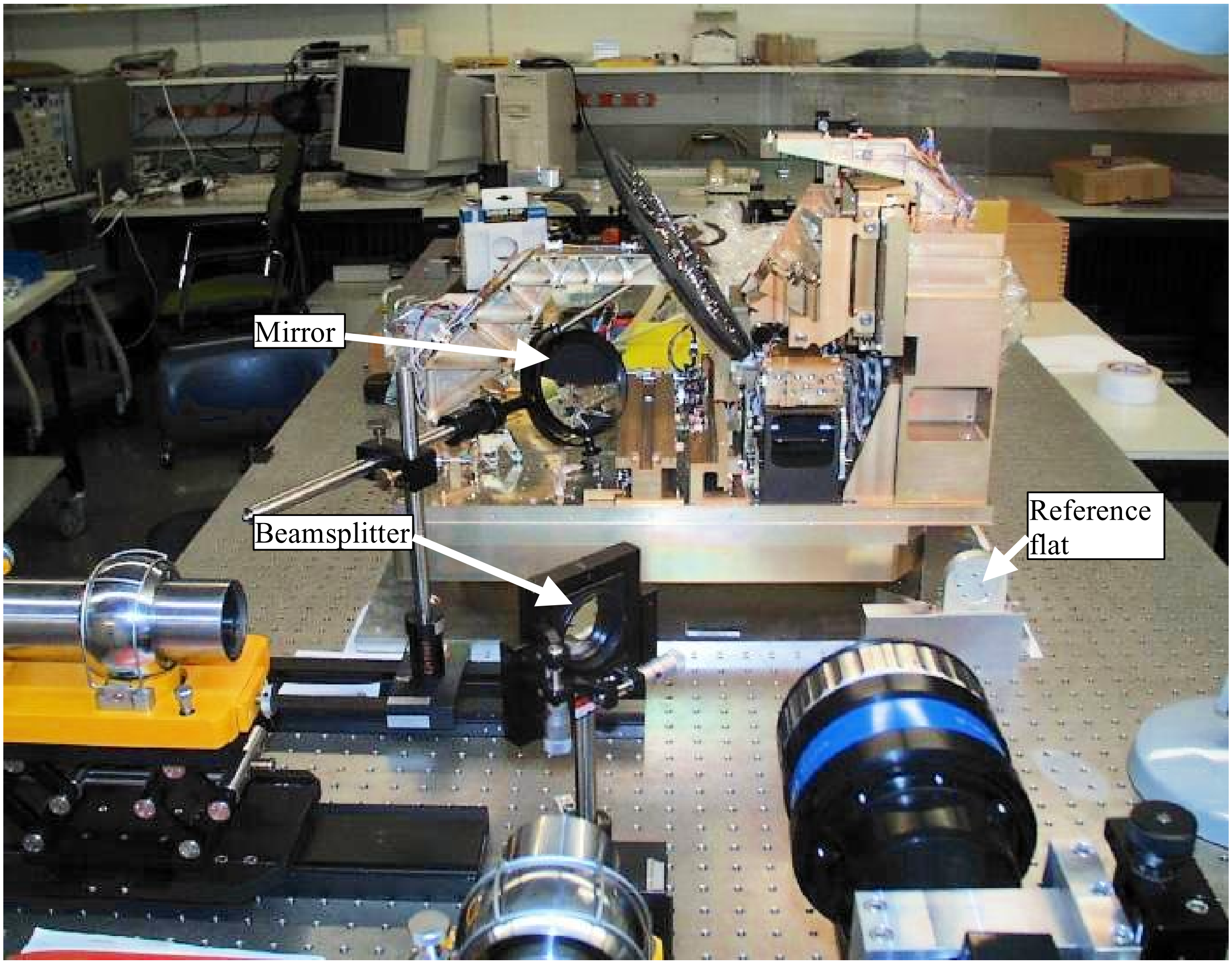

Figure 5: The alignment setup.

Figure 5 shows the setup used for aligning the MIDI cold bench. On the right is the interferometer, which is used as a light source, and to the left are the two alignment telescopes. The mirror is used to deflect the light toward the telescopes. The beamsplitter allows both beams to be viewed without having to reposition the telescopes. Shown on the right is the reference flat that is used to define the interferometer position in tip and tilt. It is usually mounted just in front of the black shutter unit.

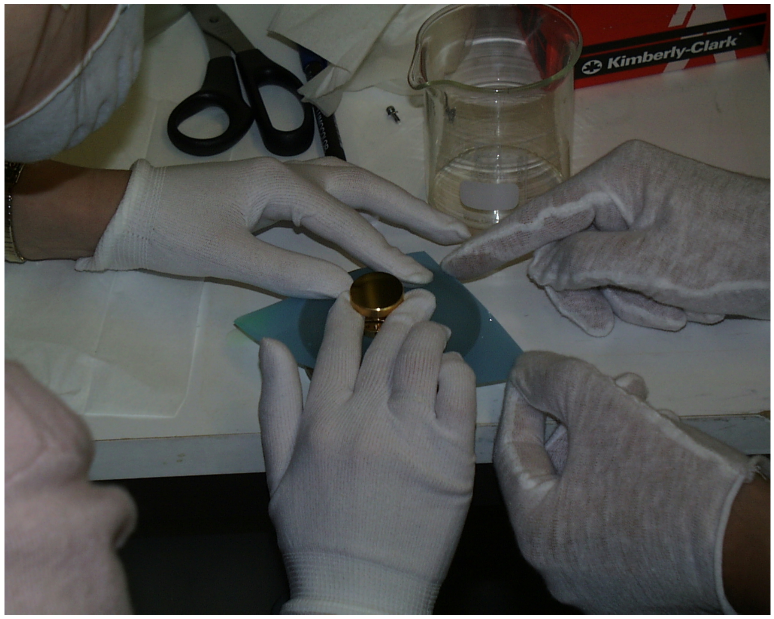

Figure 6: 'Polishing' in action.

The base of this mirror is being polished in order to reposition the mirror for alignment. The method used to remove material from the base of the mirror is actually a very fine sanding but uses optical polishing techniques. The amount of material being removed is on the micron level and if the finest sandpaper is used then the amount removed reaches the sub-micron level.

4. TEST RESULTS

The following figures show some results of tests run after alignment and during alignment. Figures 9, 10 and 11 were taken when at operational temperature (40K). The overlap in the image and pupil planes is shown and some images of the smallest triple pinholes in both imaging and dispersed modes. The last figure shows some actual fringes achieved in the laboratory.

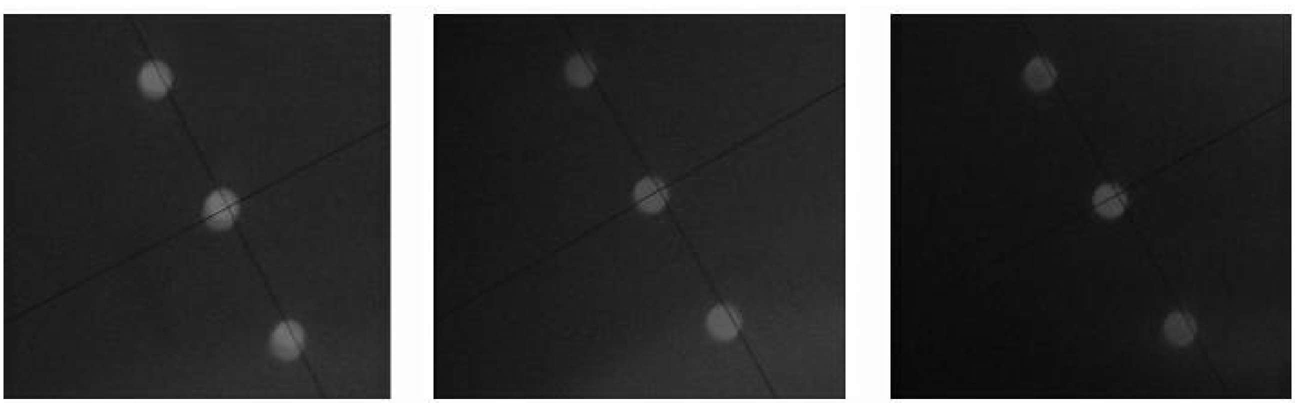

Figure 7: Overlap in the image plane.

Figure 7 shows the overlap of 2 pinhole images as seen in one of the alignment telescopes. In this case a white light lamp is used as a light source in order to fully illuminate the pinholes. The other 2 images show Beam A and Beam B in turn and their respective offsets from the telescope crosshair. The pinhole images must not be offset by more than 10% in order to get a coherent loss in this plane better than 1.2%.

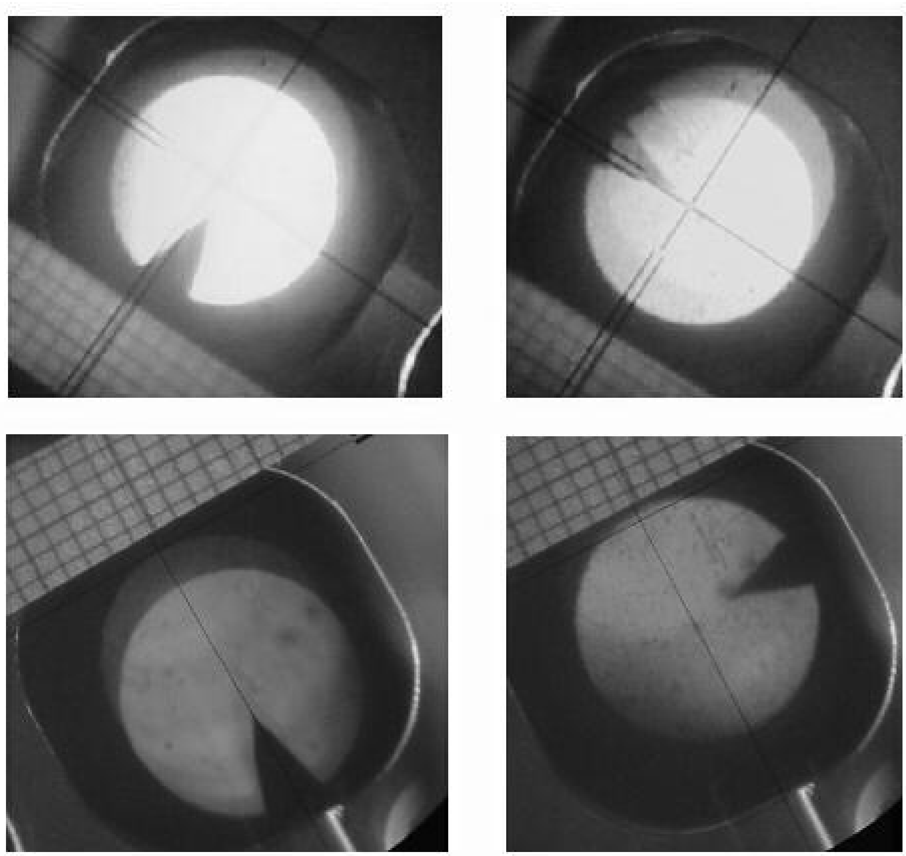

Figure 8: Overlap in the pupil plane.

The top two pictures in the above figure (Figure 8) are for interferometric beam I_1 and the lower two and for interferometric beam I_2. The left two pictures are taken with only input Beam A open. The right two pictures are taken with only input Beam B open. For the top two pictures, both the bright images should be compared but for the lower two, the fainter left-hand image should be compared to the brighter right-hand image. This is due to internal reflections in the ZnSe beamsplitter plate, which also reacts differently to visible light than to infrared light. In this plane, the pupil images should not be offset by more than 0.1mm in order to achieve a coherence loss of less than 1.3%.

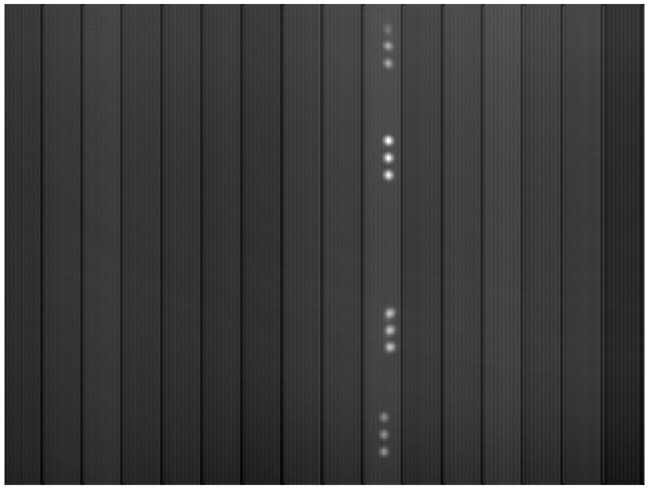

Figure 9: Detector image of all 4 beams.

A triple pinhole has been used to produce this image (Figure 9). The uppermost and the lowest triples are the photometric channels. The central 2 triples are produced by the interferometric beams. The images are also offset to the right; this is due to a misplacement of the detector. The detector can be moved, though only when the cryostat is open, and so the positions of the images can be adjusted and the best position chosen.

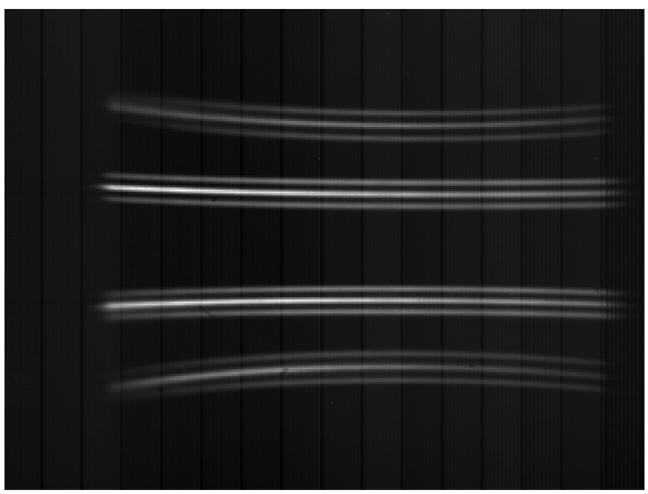

Figure 10: Detector image of all 4 dispersed beams.

The grism has been used to disperse the input light in order to create this image of a triple pinhole (Figure 10). An incoherent light source has been used so no fringes are visible. The 'banana' shape of the dispersed beams is an artifact of the camera.

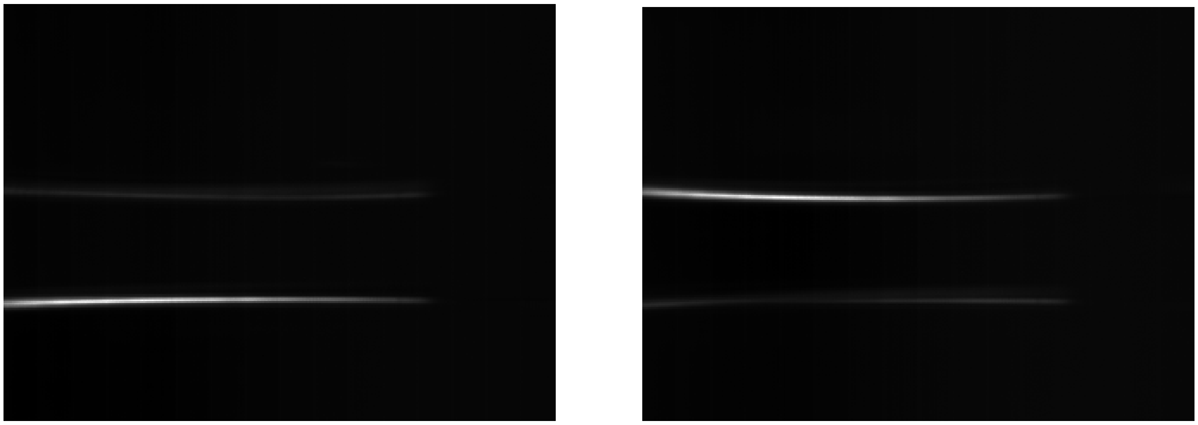

Figure 11: Dispersed fringes as seen by the detector.

The above figure (Figure 11) shows the fringes in the interferometric channels dispersed across the detector. When one beam is constructive, the other is destructive. By stepping through the optical path difference the situations can be reversed.

4 REFERENCES

1. A. Glazenborg, *Optical design of the cold bench*, VLT-SPE-MID-15821-0101, ESO MIDI PAE document
2. H. Hanenburg, *Mechanical design of the MIDI cold bench*, VLT-TRE-MID-15822-0122, ESO MIDI FDR document
3. F. Przygodda and A. Glazenborg, *MIDI Cold-Optics Alignment Manual*, VLT-SPE-MID-15821-0239, ESO MIDI PAE document
4. S. Morel, *Dismantling and Re-assembling of the Cold-Optics Bench*, VLT-MAN-MID-15821-0237, ESO MIDI PAE document