10-μm interferometry on the VLTI with the MIDI instrument: a preview

Christoph Leinert[a] and Uwe Graser[a];
Laurens B.F.M. Waters[b]; Guy Perrin[c]; Bruno Lopez[d];
Vincent Coudé du Foresto[c], Annelie Glazenborg-Kluttig[e], Jos C. de Haas[e], Tom M. Herbst[a], Walter Jaffe[f], Pierre J. Lénac, Rainer Lenzen[a], Rudolf S. Le Poole[f], Sebastiano Ligori[a], Reinhard Mundt[a], Jan-Willem Pel[g], Irene L. Porro[h], Oskar von der Lühe[i]

[a]Max-Planck-Institut für Astronomie, Heidelberg, Germany
[b]Astronomical Institute, University of Amsterdam, Netherlands
[c]DESPA, Observatoire de Paris-Meudon, France
[d]Observatoire de la Côte d'Azur, Nice, France
[e]Netherlands Foundation for Research in Astronomy, Dwingeloo, Netherlands
[f]Sterrewacht Leiden, University of Leiden, Netherlands
[g]Kapteyn Astronomical Institute, University of Groningen, Netherlands
[h]Harvard-Smithonian Center for Astrophysics, Cambridge, USA
[i]Kiepenheuer-Institut für Sonnenphysik, Freiburg, Germany

ABSTRACT

We describe principles, design and present status of MIDI, the mid-infrared interferometric instrument for the VLTI, which is planned to come into operation at the ESO Very Large Telescope Interferometer (VLTI) during the second half of 2001.

Keywords: Interferometry, thermal infrared, VLTI, MIDI

1. BACKGROUND

Interferometry with the ESO Very Large Telescope Interferometer (VLTI) on Paranal will include the four 8 m telescopes of the VLT (called 'unit telescopes' or UTs) as well as three relocatable outrigger telescopes of 1.8 m diameter (called 'auxiliary telescopes' or ATs). Observations with the VLTI will start in 2001.[1] MIDI, the mid-infrared interferometric instrument covering the astronomical N band from 8 μm to 13 μm, will be the first scientific instrument available at the VLTI. Half a year later, the near-infrared closure-phase imaging instrument, called AMBER,[2] will arrive on Paranal. A dual-feed system called PRIMA[1,3], which will add faint source and phase-referenced imaging as well as an astrometric mode to the VLTI, will follow in 2003.
The concept of MIDI has been previously presented at the SPIE conference in Kona in 1998.[4] Here, we describe the present status of this instrument.

2. RATIONALE FOR 10 μM INTERFEROMETRY WITH THE VLTI

The high thermal background and the reduced spatial resolution at this comparatively large wavelength are obvious disadvantages connected with 10 μm interferometry, and the need to cool the detector and its environment to very low temperatures adds technical complexity. Probably for these reasons, only two 10 μm interferometers have been built before. The wide-band interferometer SOIRDETE[5] could not calibrate its observed fringes because of strong fluctuations in the thermal background. ISI[6] succeded with a narrow-band heterodyne technique,[7,8] but is limited in calibrating fringes to N = -1.8 (200 Jy). Therefore direct interferometry in the 10 μm band, as envisaged by MIDI, still will be a new undertaking, promising new results or results on new type of objects. This attempt will be particularly promising at the VLTI which offers

Send correspondence to: Christoph Leinert, Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany; e-mail: leinert@mpia-hd.mpg.de

- big apertures of 8 m diameter
  (important because in the background-limited case the S/N ratio scales $\sim D^2$)
- long baselines
  (up to 130 m, corresponding to a spatial resolution of λ/D = 16mas)
- four telescopes
  (i.e. six readily available baselines)

In this combination the VLTI is unique among present-day observatories, including the Keck interferometer, which has slightly larger telescope dishes but only one 75 m baseline. These prospects led us to propose the mid-infrared interferometric instrument for the VLTI.

3. BASIC PARAMETERS DEFINING THE INSTRUMENT

Most of the parameters defining the operation of the instrument are given by the atmosphere, some by the design of the delay line optics. However, the choice to observe only one baseline at a time was made to keep sensitivity.

Table 1. Basic parameters of the MIDI instrument

Telescope diameter	UTs	8 m
	ATs	1.8 m (used for bright sources)
Baselines	UTs	47 ... 130 m
	ATs	8 ... 200 m
Resolution	λ / D for 100 m	20 marcsec
Wavelength coverage		N band (8 μm - 13 μm)
	expandable to	Q band (17 μ - 26 μm)
Field of view		$\pm$ 1$''$
Airy disk (FWHM)	for 8 m telescopes	0.26$''$
at 10 μm	for 1.8 m telescopes	1.14$''$
Sampling time for	for fringe motion	100 ms
fringe measurement	$\leq$ 1 μm rms	
Atmospheric stability	for chopping	200 ms
Differential dispersion	in 100m of air	0.9 μm (10 μm to 20 μm)
		46 μm (1.6 μm to 10 μm)
Input beam diameter	from UTs	80 mm (compressed to 18 mm)
	from ATs	18 mm
Detector	pixel size	50 μm
(320 x 240 pixels)	full well capacity	$\approx 2 \cdot 10^7$ electrons
	read noise	$\approx$ 1000 electrons
Background at UTs	from sky	$1.6 \cdot 10^{10}$ photons/sec
(in Airy disk)	from VLTI mirrors	$1.2 \cdot 10^{11}$ photons/sec
Limiting N-magnitude	with UTs	4 mag (1 Jy)
without fringe tracking	with ATs	0.8 mag (20 Jy)
Limiting N-magnitude	with UTs	9 mag (10 mJy)
with external fringe tracking*	with ATs	5.8 mag (200 mJy)

*Limiting magnitudes with fringe tracking are given for an on source integration time of 1000 s. The values are for broadband observations. Limiting brightness scales with $\sqrt{n}$ when splitting the band into n spectral channels.

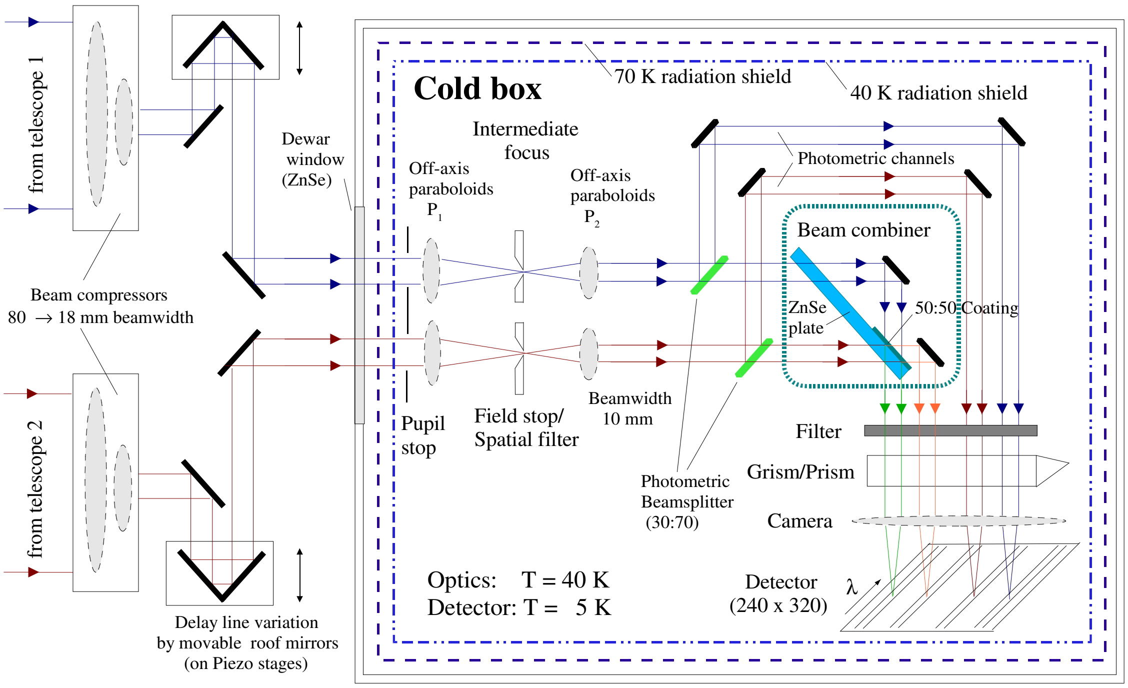

Figure 1. Optical concept

4. GOALS

The scientific promises of a mid-infrared interferometer strongly depend on its limiting sensitivity. Our goal is to achieve the sensitivity limited by the photon noise of thermal emission from the VLTI train (1.5×10^{11} photons/s per Airy disk of radius $\lambda/D = 0.26''$ with a VLTI transmission of 40%), assuming that the fringe measurement happens within one "coherence time" of 100 ms, that the instrumental transmission of MIDI is 60% and that 75% of the light fall into the Airy disk and are useable for the interferometric measurements. This gives the following performance **on the UTs** with broad band observations (limiting brightness scales like $\sqrt(n)$ when splitting the band into n spectral channels):

Point source sensitivity:	N = 4 mag (1.0 Jy)	in self-fringe-tracking mode, with 8 m telescopes and tip/tilt correction
	N = 9 mag (10 mJy)	with external fringe tracking
Accuracy of visibility:	5 %	faint sources
	1 %	bright sources, beam cleaning by spatial filtering
Phase measurement:	by external referencing	

The very large gain in sensitivity possible with a fringe tracker (fed by an adaptive optics system) cannot be overemphasised.

to reach these goals, we want to limit the instrumental loss in sensitivity to correlated flux ("visibility loss") to less than 25 %. This requires alignment of the beams to 1% of their diameter, $\pm 5''$ in their axes, and an optical quality of the surfaces of $\lambda/8$ peak-to-valley, measured at optical wavelengths, e.g. 632 nm.[10]

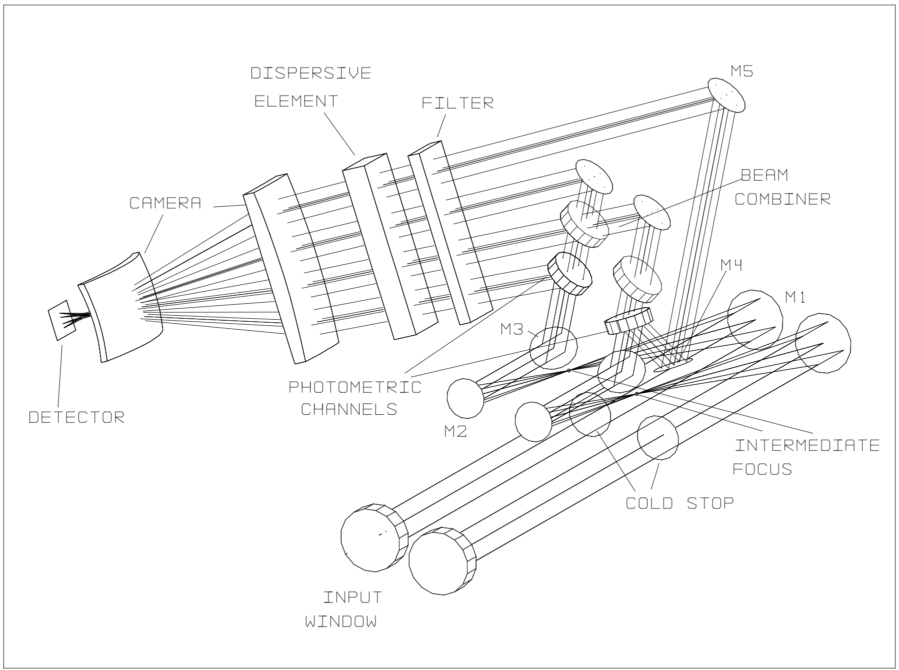

Figure 2. Design of the beam combining optics inside the cryostat. M1 and M2 are confocal paraboloids, M3, M4 and M5 flat mirrors. The beam-combining 50% : 50% coated surface is indicated by a pointer. Not shown: a cold shutter located about halfway between the cold stops and the entrance windows.

5. CONCEPT

A schematic representation of the layout of the instrument is given in Figure 1. Since radiation at 10 μm is dominated by thermal emission from the environment, most of the instruments optics has to be in a dewar and to be cooled to cryogenic temperatures (4 K - 8 K for the detector, 40$\pm$5 K for the cold bench, 77 K for the outer radiation shield). Good suppression of the thermal radiation of background and surroundings requires to design for both a cold pupil and a cold field stop inside the instrument.

We choose to have beam combination in (or close to)the pupil and to detect the signal in the image plane. This appeared to us the most promising way to support the baffling against the very high thermal background and to reduce the effects of variable pixel responsivity, which is common among mid-infrared detectors. This concept is shown schematically in Figure 1:

From the left, the afocal beams from two telescopes of the VLTI are approaching the instrument. Their nominal diameter is 80 mm, and they are reduced to 18 mm by a beam compressor provided as part of the VLTI infrastructure, represented here for simplicity by two lenses.

After the four folding mirrors of a small experiment-internal delay line, the compressed beams enter the cryostat ("cold box") through the entrance window ("Dewar window"). The telescope pupil is imaged by the VLTI delay line optics onto a cold pupil stop to provide the needed suppression of thermal emission from outside the beams. Next, an intermediate focus is formed, where different masks or spatial filters can be introduced for additional suppression of unwanted radiation. (If no spatial filters are used, the detector pixels, which are much smaller than the Airy disk, still provide an alternative way to limit the spatial region admitted for the measurement). Then the beams are recollimated and move on to combine on the surface of a 50%:50% beam splitter which coating is indicated in the Figure on the lower back side of the ZnSe plate. This is the heart of the instrument.

From the beam combiner onwards, the two interfering beams have a common optical axis. Actually, there are two of such overlaid beams, one outgoing to each side of the beam combiner. These two outputs are modulated in flux depending on the optical path difference of the interfering beams, but with opposite sense in because of energy conservation.

We measure the degree of coherence between the interfering beams (i.e. the object visibility at the actual baseline setting) by artificially stepping the optical path difference between the two beams rapidly over at least one wavelength within the coherence time of ≈ 0.1 s. This is done with help of the piezo-driven roof mirrors forming part of the small delay lines just outside the cryostat. Then, for both channels on the detector the fringe amplitude is determined from the modulating signal, usually in one of the methods known from stellar polarimetry.[9] The large and not precisely known thermal background forces us to determine the total flux separately by a chopped measurement, chopping between the object and an empty region of the sky. Dividing fringe amplitude by total flux the visibility is obtained.

For good accuracy of the visibility determination, the relative fluxes of the combining beams have to be known at the time of the fringe measurement. To this end, part of the incoming light can be extracted out of both of the incoming beams before beam combination, and these socalled 'photometric beams' are also imaged onto the same detector as the interferometric signal.

Spectral resolution is obtained by filters or with a prism or grism in the parallel beam after beam combination. This provides moderate spectral resolution and at the same time keeps the detector from saturating.

In principle, for the measurements with MIDI the full interferometric field of $\pm 1''$ is available simultaneously. This is a small area on the sky, but the point to emphasise is that there is at all an interferometric field beyond the Airy disk of a single telescope.

6. DESIGN

6.1. Detector

For detector we use the 320 × 240 Si:As Impurity Band COnduction (IBC) array manufactured by Raetheon. Pixel size is 50 μm × 50 μm, peak quantum efficiency over the 2-28 μm response range is >40 %, the active area >95 %, and less than 1 % bad pixels are expected. Power consumption is ≈60 mW, and maximum frame rate 700 Hz. Detector control is quite flexible but complicated by the large number of controllable parameters. Our laboratory tests will have to verify the critical quantities of full well capacity of 1.1×10^7 e^- and read noise of 1100 e^-, as they are given by the manufacturer for the more sensitive so-called "high-gain" mode. It is unfortunate that there should be only a factor of three between the Poisson noise corresponding to full well signal and the read noise. This will require fine tuning of signal size for best S/N ratio.[15]

6.2. Optics

The design of the cold optics[16] is shown in Figure 2. For focal plane mask, filter, dispersing element, and camera different elements can be selected by moving a slider or a wheel.

cameras:	field camera	λ/D = 3 pixels
	spectroscopic camera	λ/D = 1x2 pixels (two in spatial direction)
	pupil viewing camera	pupil diameter = 40 pixels
dispersing elements	grism	resolution per pixel = 520
	prism	resolution per pixel = 60
	none	for observations with filter
filters	10 filters	narrow-band to full N band
focal plane	open	full $\pm 1''$ field
	slits	1-4 λ/D
	diaphragms	1-4 λ/D
	10 μ monomode fiber	best beam cleaning[17]

In addition, special setups are available for testing and alignment. The positions for future 20 μm optical components already are provided, allowing an easy upgrade to this second wavelength range.

6.3. Cold bench

Figure 3 shows how the mechanisms associated with the different optical components are distributed within the 40 K envelope, and how they are mounted on the so-called "cold bench" base plate. The main design criterion has been to have a stable, stress-free construction out of one single material, in this case the aluminum alloy Al 6061-T651, where the annotation T651 indicates a special annealing heat treatment. Homologous contraction during cooldown (0.42% from room temperature to 35 K) will preserve the alignment of the optical paths within the 40 K envelope, deferring the alignment and adjustment tasks to the warm parts of the instrument. The 40 K radiation shield connected to the cold bench and the outer radiation shield connected to a liquid nitrogen tank at 77 K are not shown in Figure 3 for clarity, nor is the box-shaped cryostat. The outer dimensions of this cryostat are partially outlined by the the front end of the eight motor/encoder units and by the larger one of the two flanges on the closed cycle cooler. With dimensions of 850 mm x 598 mm on the table, 804 mm height, and a weight of 300 kg - 350 kg this is an instrument of moderate size.

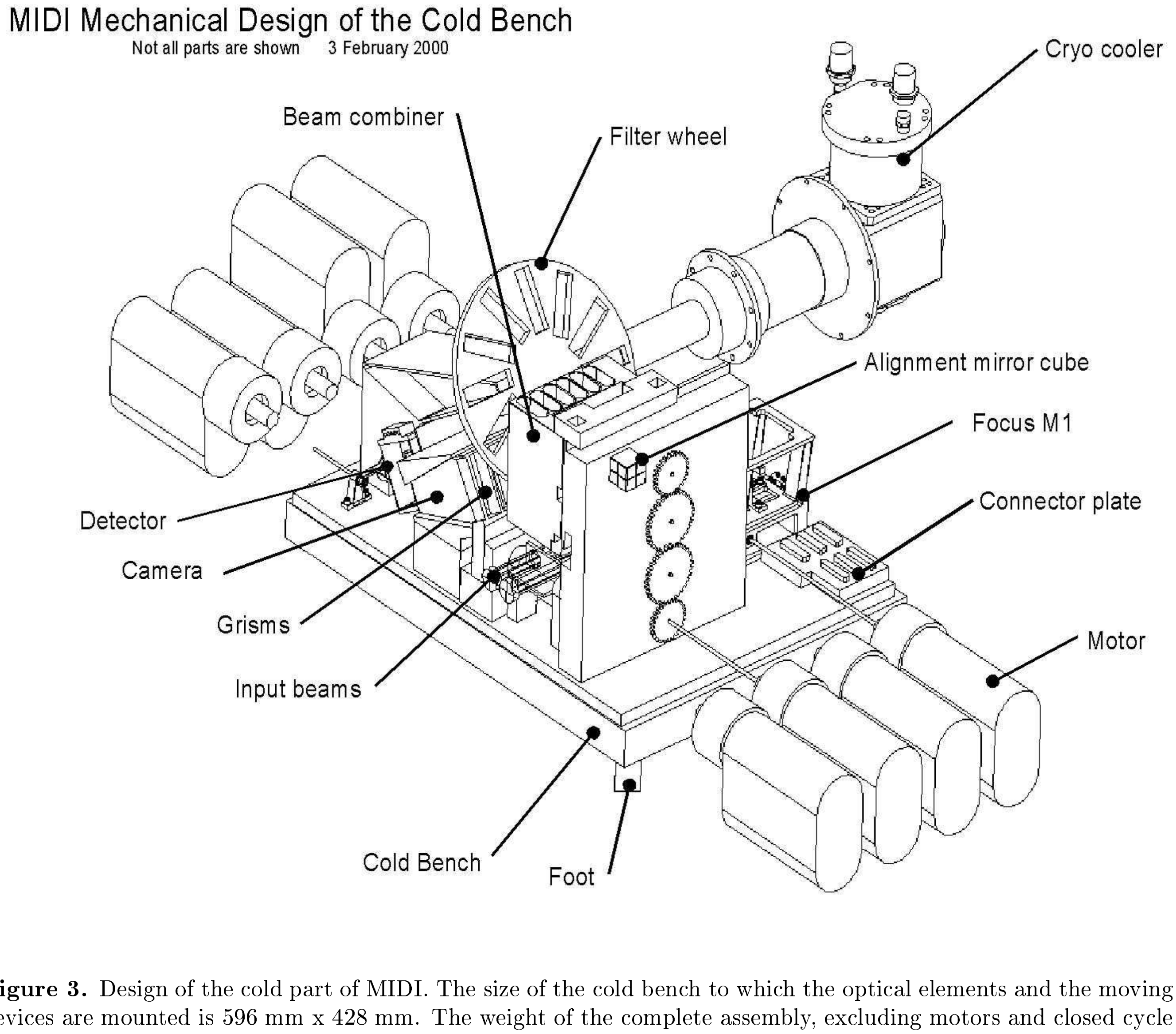

Figure 3. Design of the cold part of MIDI. The size of the cold bench to which the optical elements and the moving devices are mounted is 596 mm x 428 mm. The weight of the complete assembly, excluding motors and closed cycle cooler, is 28.9 kg.

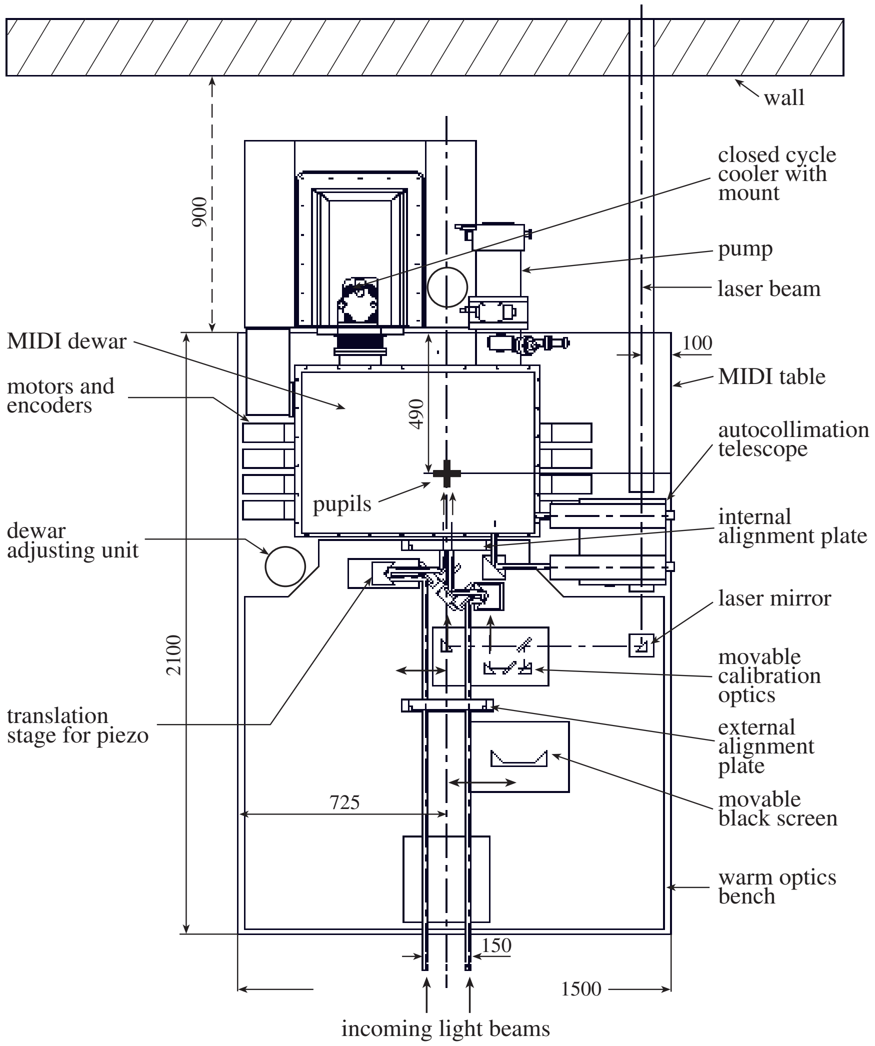

Figure 4. MIDI setup in the interferometric laboratory. The optical table carrying the cryostat, external optics and auxiliary equipment has dimensions of 1500 mm x 2100 mm.

6.4. MIDI in the interferometric laboratory

Figure 4 shows how the cryostat,[18] with turbomolecular pump mounted, is arranged on the optical table of MIDI in the interferometric laboratory. The closed-cycle cooler, connected to the crystat by a bellow (appearing black) is rigidly mounted to a separate massive block of cast material just next to the MIDI table. With respect to Figure 4, the delay lines of the VLTI would run left/right near the bottom the page. Dedicated beam compressors more to the right of the MIDI table in the interferometric laboratory keep the image of the telescope pupils on the cold pupil stops inside the MIDI dewar with alongitudinal precision of ≈1 cm. The beams from the telescopes – any telescope pair can be chosen for the two input beams – approach the crystat from the lower part of the figure, passing over the so-called "warm optics bench", a separate breadbord with two corners cut out, and mounted directly on the large optical table. The small four-mirror internal delay lines close to the dewar are laid out asymmetrically in order to compensate for asymmetries in the way the beams are directed towards the instrument. The two alignment plates on the warm optics bench are removed during the observations. In addition to the calibration provided by the VLTI system LEONARDO, which is situated a couple of meters upstream of the instrument, MIDI has two calibrating units of its own: a black-body screen which can be moved in and out of the field-of-view of the instrument, and a laser in the neighbouring room, the radiation of which can be made replacing the interferometric beams by moving in a small plate carrying the necessary optics. The path of the laser beam through the laboratory wall to the warm optics bench can be seen in the upper right of the figure.

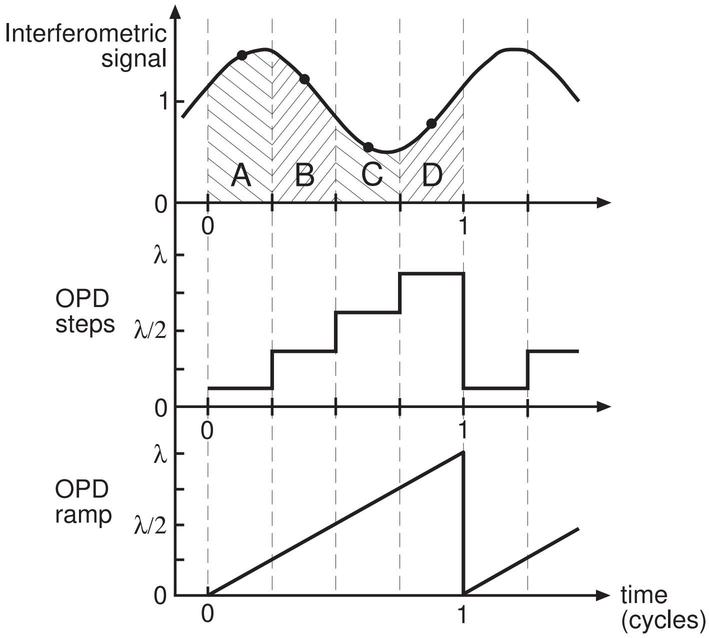

Figure 5. The standard fringe sampling mode ("ABCD method").
The optical path difference (OPD) between the interfering beams is modulated by the equivalent of one wavelength, either by having four steps, separated by $\lambda/4$ (middle panel, measurement taken at dotted position), or by a continuous linear sweep (ramp) one wavelength (lower panel, integration over the shaded interval); and this modulation pattern is repeated as needed. In both cases, the phase of the modulating signal signal is equal to $\tan^{-1}[(A-C)/B-D)] + \pi/4$, and the visibility proportional to $\sqrt{(A-C)^2+(B-D)^2}$, with proportionality factors of 1.0 and $2\sqrt{2}/\pi$, respectively.

7. OBSERVING WITH MIDI

Because 10 μm arrays have the bad reputation of unstable flat fields, the main observing modes for MIDI are using on-the-pixel comparison for background subtraction. In the so-called "ABCD" method (see Figure 5) the optical path difference (OPD) between the incoming beams is stepped or scanned through one wavelength. The detector pixels in the Airy disk of a sufficiently unresolved object then will experience a sinusoidal flux variation, with four measurements being taken per period. Since the method works from differences between these flux values measured on the same pixel(s), it is comparatively insensitive to flatfield effects.

If the interferometric measurements are performed with dispersion, different ways of deriving the modulation can be applied. For non-zero OPD, constructive and destructive interference will follow each other when moving along the spectrum. This gives rise to a "channeled" (i.e. transversed by dark lines) appearance of the spectrum. The distance between adjacent minima or maxima in the channeled spectrum is constant in optical frequency space and inversely proportional to the momentaneous OPD value. With some knowledge or assumption on the nature of the OPD fluctuations and on the wavelength dependence of visibility for the object then both, the OPD history during the measurement and the object visibility can be obtained by a fitting procedure.[11] The expectation is that by the associated increase in effective integration time, when compared to self-fringe tracking measurements, one magnitude or more can be gained in limiting sensitivity. These so-called "coherent integration" procedures, which will as a side effect allow slow (a few s) OPD tracking, will also be available for observations with MIDI.

Table 2 gives an indication how the limiting magnitude for self-fringe tracking depends on the circumstances of the observations. Read noise and transmission of optics lead to the result that the achievable S/N ratio and hence limiting magnitude depends on spectral resolution, which should not occur in the truly background limited case.

Table 2. Estimated point source sensitivities for 100 ms integration time

option	range	$\Delta\lambda$	$\lambda/\Delta\lambda$	Limiting N band magnitude per $\Delta\lambda$	per 1/3 of range
full field	narrow-band filters	0.12 μm	80	2.0	–
white light	8.0-13.0 μm	5.0 μm	2	4.3	–
low resolution	7.0-14.0 μm	0.32 μm	30	2.8	3.9
medium resolution					
– full N band	7.5-14.5 μm	0.044 μm	260	1.4	2.9
– upper N band*	10.0-13.5 μm	0.022 μm	530	0.8	2.9
– lower N band*	7.4-10.5 μm	0.020 μm	450	0.8	2.9

*these grisms have not yet been funded

Therefore, best sensitivity, N = 4.3 mag (slightly less than 1 Jy) may be expected for broad band observations. On the other extreme, one could decide to observe with fibers (60% coupling efficiency), using the grism with photometric channels (taking 35% of the light) and reading out the detector at its maximum rate of 4 ms per measurement. The resulting limiting magnitude for self-fringe tracking then would be N = -1.1 mag (110 Jy) for an individual resolution element and N = 0.1 mag (43 Jy) for the combined signal of 10 resolution elements.

In all cases, external fringe tracking over a time interval T will improve the sensitivity considerably, theoretically by at least a factor of $\sqrt{T/0.1s}$ or already by 2.5 mag for even a modest 10 s interval of fringe stabilisation.

8. SCIENCE PROGRAMME

The scientific Potential of MIDI observations will be discussed in more detail elsewhere in these conference proceedings.[13] Apart from the spatial resolution given by the geometry of the VLTI array, it strongly depends on the sensitivity of the instrument and on the accuracy of visibility calibration. Before fringe tracking will be available on the VLTI in 2003, the limiting magnitude will be N = 4 mag (1 Jy) at best (see Table 2). When fringe stabilisation becomes available, fringe motion due to atmospheric turbulence will be compensated, and interferograms can blindly be added together without smearing the fringe signal. A total integration time of 15 min should improve the sensitivity by a factor of 100 to N = 9 mag (10 mJy). With this kind of performances, extragalactic studies come within reach of the instrument. However, it has to be stressed that these are point source sensitivities, related to correlated flux, and a somewhat extended source may have to be much brighter to produce measurable fringe signals. Moderate accuracies of ±5% - 10% in visibility are expected in general, although on bright sources, using photometric monitoring of the input beams by means of the photometric channels of the instrument, accuracies of

Table 3. Outline of first scientific observations planned with MIDI

Objects	Topic	Number with/ (without) fringe tracker	required telescopes
Active galactic nuclei	dust tori	5* (≈12)	UTs only
Young stellar objects	geometry and disk structure	6 (≈15)	UTs mostly
Extrasolar planets	detection by shift of light center	(2)	UTs only
AGB stars	spatial distribution of dust components	≈10	
Smaller programs	Galactic center, hot stars, very low mass stars	(≤5)	UTs mostly

* NGC 253, NGC 1068, NGC 3758, NGC 5128, Circinus (J1413-6520)

1% appear feasible. This will require a similar accuracy in total flux determination, which has to be achieved by chopping against an empty part of the sky, a complicated procedure within an interferometer.

From these considerations, we identified as main goals for the first two to three years of observations with MIDI (see Table 3) the study of nearby active galactic nuclei and the study of circumstellar material around young stars. Defining the spatial distribution of different dust components around asymptotic giant branch stars will be another important topic. Following the orbits of close young binaries for mass determination and studying the history of dust formation in red giants are also promising studies, but because of the long time base needed they are less well suited as one of the first science programms. Measuring the spatial separation of an extrasolar planet from its central star is an exciting project, but very, very challenging for an instrument like MIDI, because the signature will be well below 1% even for the biggest extrasolra planets known.[14] Finally, small projects on individual targets of astrophysical interest will help to demonstrate the scientific capabilities of the instrument.

9. STATUS AND SCHEDULE

MIDI is being built by a european consortium led by the Max-Planck-Institut für Astronomie in Heidelberg (PI team),including astronomical institutes in the Ntherlands coordinated by the Netherlands School for Astronomy (Co-PI), Observatoire de Paris (Co-PI for the French contribution), the Kiepenheuer-Institut für Sonnenphysik in Freiburg, the Thüringische landessternwarte in Tautenburg, and Observatoire de la Côte d'Azur (chair of the science group).

The final design review for the optics has been passed in July 1999, the remaining parts of the final design review happened at the end of February 2000. Development of hardware and software proceeds with a scheduled begin of integration of the instrument in Heidelberg in October 2000. After shipment to Paranal, commissioning with the siderostats of the VLTI is planned for autumn 2001, with the 8 m telescopes at the beginning of 2002, and with the 1.8 m auxiliary telescopes later the same year. MIDI therefore should begin science observations in the first half of 2002.

10. OUTLOOK

The possible future development of the instrument includes

- Addition of a wavelength band at 20 μm. Space for the necessary optical components has already be reserved in the optical and mechanical design.
- Phase measurements by external referencing. This has to await the implementation of the VLTI subsystem PRIMA[1,3], which will become operational in 2003.
- High spectral resolution ($\lambda/\Delta\lambda$ = 10 000), to allow gas phase and kinematical studies.
- Simultaneous measurements on several baselines for closure phase imaging.
- A nulling option. The very accurate beam cleaning to be expected from the use of single-mode fibers should be an advantage when developing this option.[12]

While the first two upgrades can be obtained with modest modifications on the present instrument, the three latter ones will require substantial changes or a complete redesign.

ACKNOWLEDGMENTS

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