Keynote Address

DESIGN AND ALIGNMENT OF THE MIPAS FOCAL PLANE SYSTEM

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ABSTRACT

The Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) is selected by ESA for the ENVISAT-mission, scheduled for launch in 1999.
The instrument will measure the concentration of atmospheric trace gases in the earth atmosphere in a spectral region from 4.15-14.6 μm. MIPAS consists of scan mirrors, a telescope, a Michelson Interferometer, an optical reducer and a focal plane assembly.
The optical reducer consists of a 2 concave and 1 convex mirror system. The focal plane assembly consists of a configuration of mirrors and dichroics, with which the spectral range is divided in 4 spectral bands.
TNO Institute of Applied Physics has designed the optical/mechanical system and after manufacturing of the components has aligned the system with high accuracy. The design and alignment of this system is described.

Keywords: Optical design, Michelson interferometer, alignment.

1. INTRODUCTION

Some years ago an intense activity started to develop in Europe instruments for observation of the atmosphere from space. These instruments must measure ozone and other trace gases in the atmosphere with high accuracy. For measurements in the 240 - 800 nm spectral range in 1995 GOME[1,3] (= Global Ozone Monitoring Experiment) was launched on board of the ERS-2 satellite and for 1999 the launch of SCIAMACHY[2,4] (= Scanning Imaging Absorbtion spectrometer for Atmospheric CHartographY, spectral range 240 - 2400 nm) on board of the ENVISAT is scheduled. For measurements in the infrared part of the spectrum MIPAS[5,6] (= Michelson Passive Atmospheric Sounder) is one of the instruments, that has been selected by the European Space Agency (ESA) for the ENVISAT mission.
MIPAS is an interferometer and will measure atmospheric trace gases from the upper troposphere until the lower thermosphere (5 - 150 km).

The spectral range of MIPAS covers the infrared from 4.15 - 14.6 μm while the spectral resolution is better than 0.034^{-1} cm. Measurements on a global scale of various gases including ozone and CFK's will be possible. The instrument is being developed by the main contractor DASA (Germany) and a number of subcontractors.
The optics of MIPAS consists of 2 scan mirrors, an anamorphotic telescope, a dual output Michelson interferometer (giving 2 parallel output beams), an afocal reducer (AFR) and a cold focal plane inner structure (FIS). The AFR and the FIS are being developed in the Netherlands by a consortium, that consists of Fokker Space, the Laboratory of Space Research (SRON) and the TNO Institute of Applied Physics (TPD).

TPD is responsible for the design and manufacture of the opto-mechanical part of the AFR and the FIS.
The integration and the (pre-)alignment of the qualification model of AFR and FIS has been performed by the TPD.
In the following chapters the design of the AFR and FIS and the integration/alignment are described in more detail.

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2. OPTO-MECHANICAL DESIGN

2.1 Starting points and specifications

The AFR has to reduce the size of the beams of the interferometer.
Size of input beam: 50 x 25 mm^2
Beam divergence: 9.0 x 5.4 $mrad^2$
Reduction: 5.0 ± 0.1
This means for the output beam:
Size: 10 x 5 mm^2
Divergence: 45 x 27 $mrad^2$
The purpose of beam reduction is:
- Reduction of the dimension of the (cooled) FIS. The temperature of the FIS is 70 K.
- Decrease of sensitivity of misalignment of the cold FIS w.r.t. the warmer parts of the instrument.

In the FIS each of the 2 beams of the interferometer is separated in 4 spectral bands. The wavelength ranges of these bands are given in table I.

Channel	Wavelength range	Channel	Wavelength range
A1	10.3 - 14.6 μm	A2	8.55 - 14.6 μm
B1	6.9 - 9.8 μm	B2	6.9 - 8.25 μm
C1	5.7 - 6.3 μm	C2	5.7 - 6.3 μm
D1	4.15 - 5.5 μm	D2	4.15 - 5.5 μm

Table I: Spectral bands

Spectral separation is performed by dichroics.

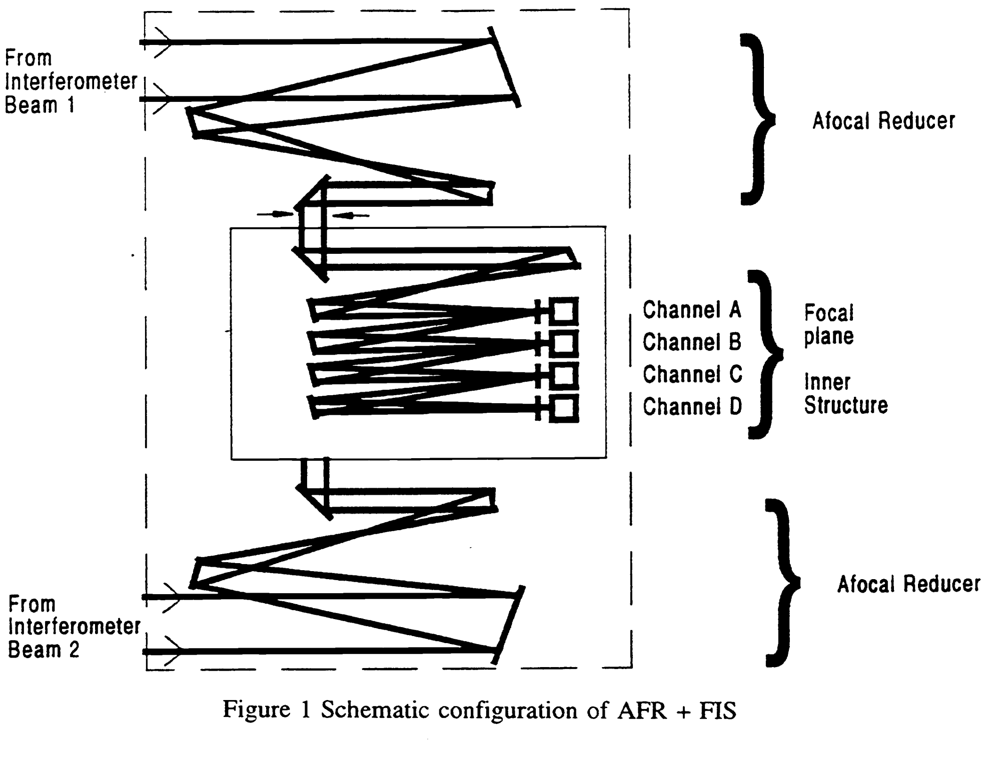

Figure 1 Schematic configuration of AFR + FIS

The optical layout of the AFR and one part of the FIS is schematically given in figure 1.
Concerning the optical configuration the following remarks must be made:

- Critical aperture stops are co-located with intermediate pupil and field images to reduce background/straylight.
- The FIS entrance aperture is imaged on the detector. The size of the aperture (9 x 4.5 mm^2) is 10% less than the pupil image (10 x 5 mm^2).
- The field of view (FOV) is imaged on a (cold) entrance aperture inside the FIS. This aperture is slightly oversized (w.r.t. the FOV of the telescope).
- The transmission of each spectral band must be > 60% and the influence of polarisation of the incoming beam on the transmission must be minimal.

2.2 Afocal reducer

The optical layout of the AFR is presented in figure 2. It is an all reflective configuration, consisting of a concave primary mirror (ellipsoidal), a convex secundary mirror (spherical), a concave tertiary mirror (spherical), and a flat beam folding mirror, to direct the (parallel) exit beam to the FIS. The primary and secondary mirror image the FOV at an intermediate stop. The tertiary mirror collimates the beam again.
The beam size is reduced by a factor 5 and the exit pupil of the interferometer is imaged at the entrance aperture of the FIS.
Both AFR's are identical and the exit beams are in line with each other. This means, that for alignment as final check a test beam, that enters through one aperture leaves the system after passing the 2 AFR's through the aperture of the second AFR. The quality of this beam can be measured (direction, collimation).

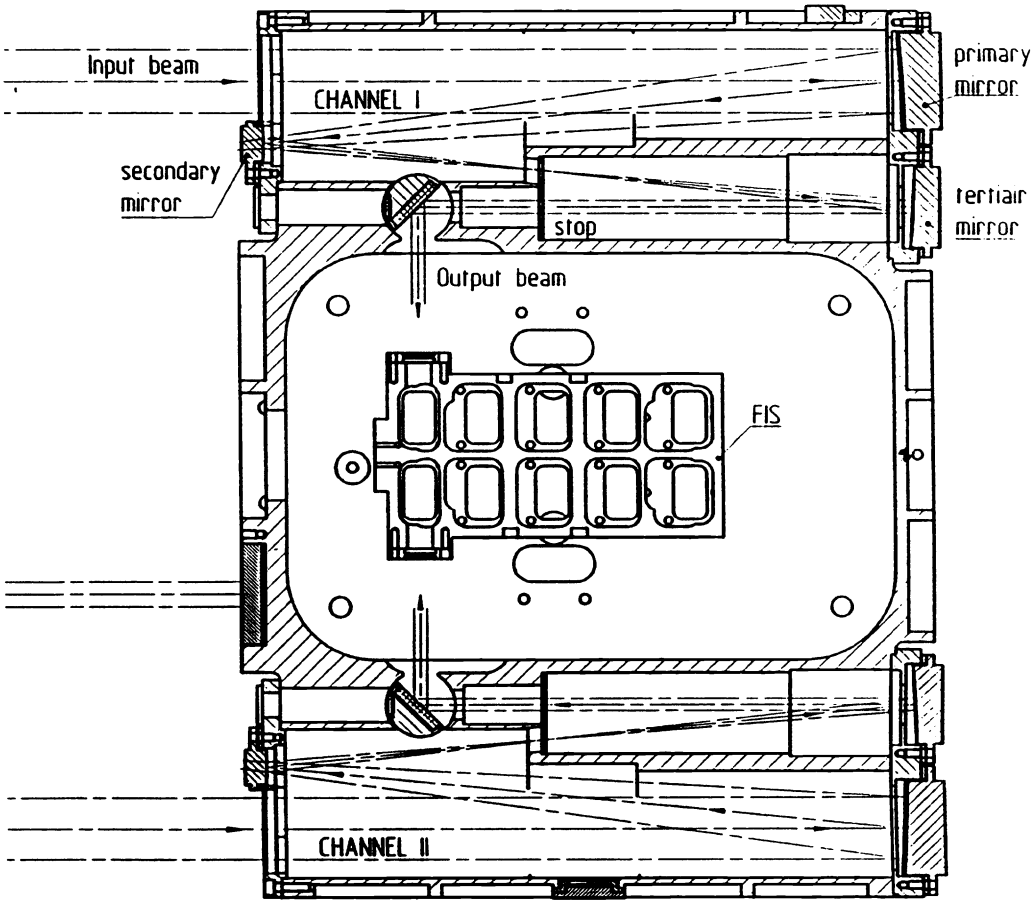

Figure 2 Afocal reducer

The structure of the AFR and the optical components (mirrors), are made of aluminium. The structure is made of one monolithic box in which the optical components are integrated. In the center of the box sufficient space is created to locate the FIS box. Because both structure and optical components are made of Aluminum a very stable, rigid and temperature insensitive system is created.

The mirrors that are diamond turned and gold coated are mounted to the structure from the outside, while for fine adjustment shims are used. In this way a good accessibility for alignment/adjustment is created and replacement of a component is relative easy.
Because of the "all-aluminum" design alignment can be performed at room temperature and using visible light.

2.3 Focal plane inner structure

The FIS is located in the center of the AFR structure, in between both AFR configurations.
The optical layout of one part of the FIS is presented in figure 3.
The main functions of the FIS are the following:

- Separate the incoming beam in 4 spectral parts.
- Produce an intermediate field image, that is common to each spectral channel (in the "coldstop").
- Reimage the FOV on the aperture in front of the Ge-lens just before the detectors.
- Image the entrance aperture on the detectors.

The optics consists of a flat beam folding mirror (1), a parabolic mirror (2) for reimaging the FOV in the "cold stop" and for reimaging the entrance aperture, 4 parabolic mirrors (3) to relay the FOV on the dichroics, 3 curved dichroic beamsplitters (4) to separate the spectral bands and to relay the image of the entrance aperture and 4 lenses of germanium (5) to reimage the aperture on the detector.
Following the lightpath in figure 3:

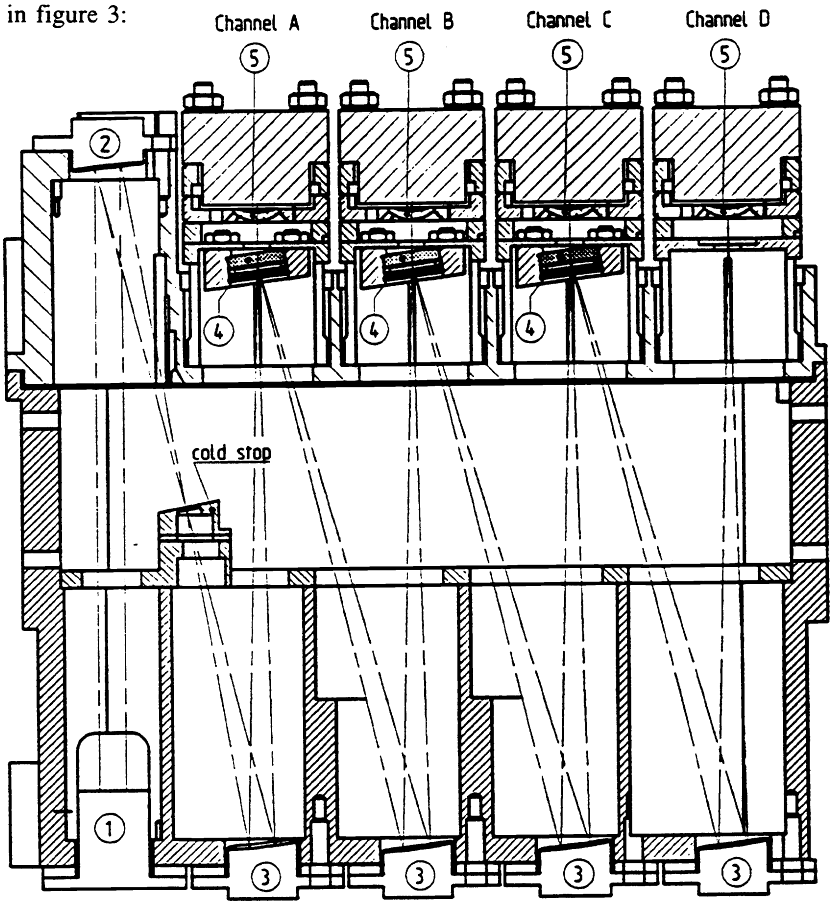

Figure 3 Focal plane inner structure

A parallel beam enters the FIS through the entrance aperture (9 x 4.5 mm^2). Via flat mirror (1) and parabolic mirror (2) the beam is focussed on a cold stop (the common intermediate field image). The same parabolic mirror (2) reimages the aperture stop near mirror (3) of channel A. This mirror reimages the cold stop on the dichroic beamsplitter (4) of channel A. This dichroic component is in reflection a curved mirror, reflecting the short wavelength range and reimaging the aperture stop image near mirror (3) of channel B.
In transmission the dichroic mirror acts as a long pass filter. The germanium lens (5) of channel A reimages the aperture on the detector. This reimaging of the FOV and the aperture is repeated by the components (3) and (4) in the other channels.

A few remarks about the design of the optics:

- In the main lightpath the optical components are used in reflection (mirrors, dichroics). This makes alignment of the optical train with visible light (He-Ne laser, $\lambda = 633$ nm) possible.
- The optical quality of the system is close to the diffraction limit. The only chromatic errors are introduced by the transmission components (ZnSe of the dichroics and germanium lenses) close to the detector.
- The optical efficiency is large, being determinated by the reflectivity of the mirrors (gold coating, R > 98%), the reflectivity or transmission of the dichroics (transmission 92 - 98%, reflection 92 - 99%) and the transmission of the germanium lenses (T > 90%). This high efficiency and the small angle of incidence on the optical components imply, that the polarisation of the optical train can be neglected.
- The dichroics are used at a relative small angle of incidence (7.5 degrees), which reduces the complexity of the dichroics design and the polarisation effects.

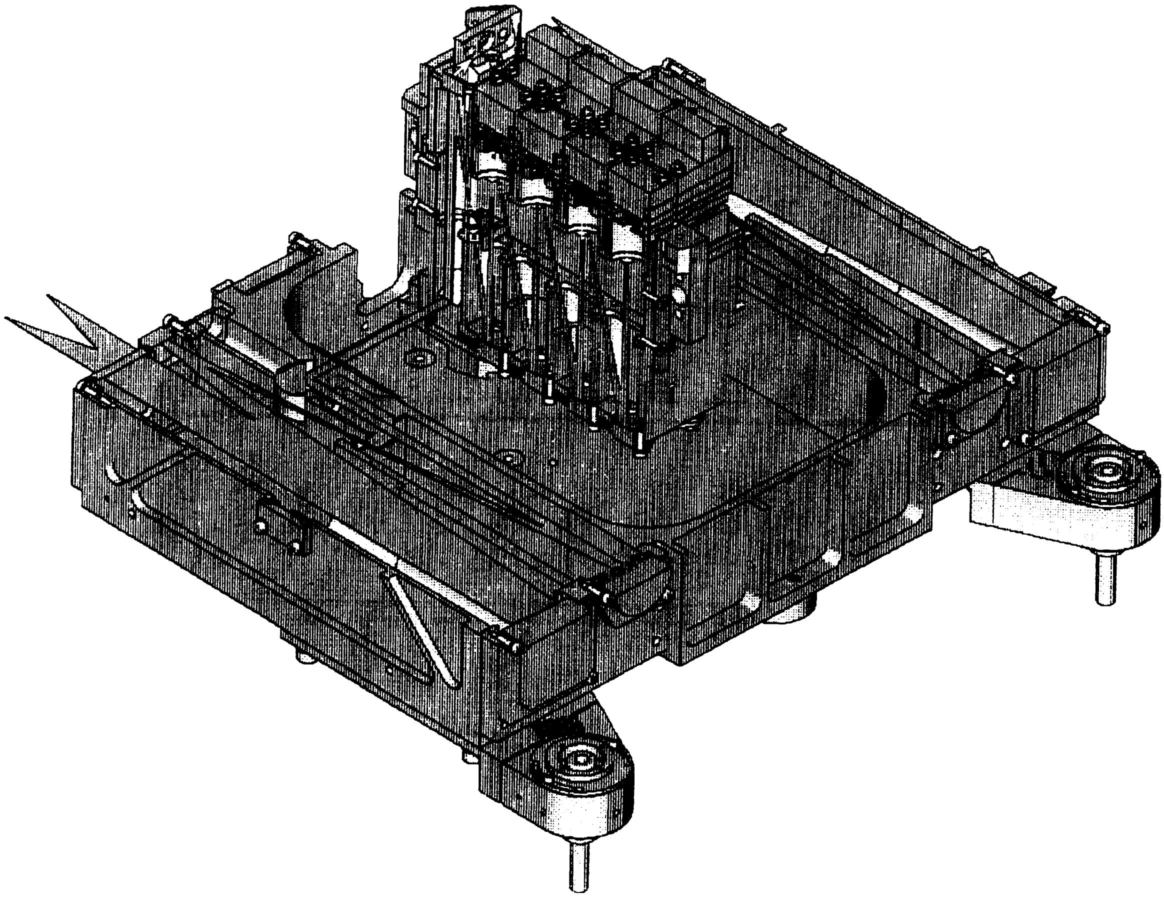

Figure 4 CAD figure of AFR and FIS.

For the mechanical design of the FIS partly the same philosophy is used as for the AFR. Both the structure and the mirrors are made of aluminum leading to a mechanical stable and thermal insensitive structure. Also the mirrors can be mounted from the outside and adjustment is performed by using appropriate shims. A separate part is the detector unit. It consists of a titanium pedestal, that contains the dichroic mirror and a part, that contains the germanium lens and the detector. In the design provisions have been made to ensure an easy and accurate replacement of detector lens assembly (DLA). Because of the operating temperature difference between the AFR (170 - 320 K) and the FIS (70 K) they are thermally isolated by means of 6 glass-fiber rods. The mechanical/thermal design is such, that a change from room temperature to operating temperature has a minimal effect on the mutual alignment.
The DLA itself, to which the detector and the germanium lens are mounted is made of Titanium. At the rear side a Hg : Cd : Te detector is connected. This Titatium DLA is connected to the main structure by means of an Aluminum tube with spring leaves to absorb the difference in thermal expansion.
In figure 4 an overall CAD impression of the AFR/FIS system is given.
The mass of the overall optical/mechanical system amounts to less than 8 kg.
The mechanical envelope of the system is about 375 x 300 x 250 mm^3.

3. ALIGNMENT

3.1 Introduction

At TNO-TPD the adjustment and alignment of the optical components in the AFR and the FIS have been performed. This activity took place in an optical clean room of the TPD in a class 500 cleanliness environment. The alignment setup was mounted on an optical bench, while the structure of AFR or FIS was mounted on a turn-tilt table, which has an angular accuracy/reproducibility of about 1 arc sec.
The AFR and the FIS were adjusted and aligned separately. As already mentioned the alignment was performed in the visual spectral range, using a He-Ne laser as light source (λ = 633 nm) and at room temperature. Also special tools were developed to make alignment/adjustment easier and more accurate.

3.2 The alignment of the AFR

The starting points are:

1. Each AFR is first aligned separately with respect to one parallel incoming beam (≈ 1 arcsec) that is large enough to cover both AFR ports (ϕ = 400 mm).
2. The requirements of the output beam of the AFR w.r.t. the entrance aperture of the FIS are:

Position	:	0.1 mm
Pupil co-alignment	:	± 70μm
Direction	:	± 2.0 mrad
Co-alignment	:	± 2 mrad

3. After alignment of the separate AFR's the total AFR block is checked.
   Here light enters through one AFR port and after passage of the 2 AFR's leaves through the second part. The quality of this beam is checked.
4. Alignment/adjustment starts with applying the nominal shims at the mirrors. When necessary shims are replaced by thicker or thinner ones. Adjustment in cross direction is possible by the oversized holes in the mirror mounting flange.

For the alignment of the AFR some auxiliary tools were developed, such as:

- Alignment mirror to determine the direction of the incoming beam.
- Alignment bracket.
  This bracket and the AFR is mounted on a baseplate. This bracket contains 2 holes, that determine the location of the entrance ports and a hole to pass the light through to the alignment mirror (see figure 5).
  The location of the entrance ports on the bracket coincides with the entrance pupil of the AFR.

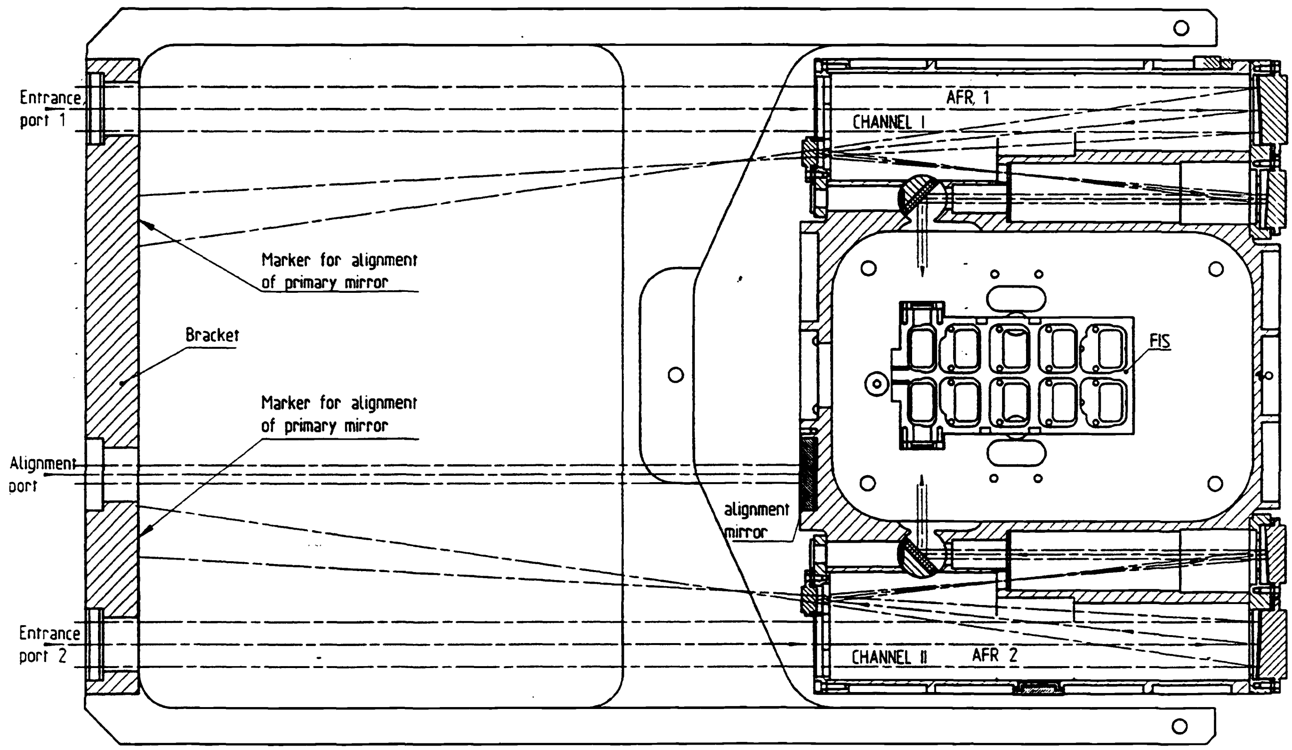

Figure 5 AFR & alignment bracket

- Dummy FIS, that is mounted in the center of the AFR structure. The dimensions of the dummy FIS, including the location of the entrance aperture are representative for the real FIS.
  The dummy FIS is used to check the position of the outgoing beam of the AFR.

Besides of these special tools optical techniques as autocollimation are used to measure direction and parallellism of optical beams.

The adjustment and alignment was performed in the following steps:

1. Bracket and AFR are mounted on a baseplate and aligned with an accuracy of about 1 arc min.
2. Assembly is aligned w.r.t. incoming beam with the reference mirror on the AFR (autocollimation, accuracy ca. 1 arcmin).
3. Primary mirror is adjusted, starting with nominal shims. Criterium for adjustment: reflected beam through center of the hole of the secondary mirror. At the inner side of the bracket a mark is made, on which the reflected beam is directed (nominal position).
4. The secondary mirror is adjusted, starting with nominal shims. Criterium for adjustment: reflected beam through center of the hole of the tertiary mirror.
5. The tertiary mirror is adjusted, starting with nominal shims. Criteria for adjustment: direction and quality of the parallel output beam.
6. The flat beam folding mirror is adjusted also starting with nominal shims.
   Criteria for adjustment:
   - Direction of output beam (tested via autocollimation).
   - Location of output beam (tested with dummy FIS).
   - Quality of beam: already tested in step 5.

These steps are subsequently applied to both AFR's.
The adjustment/alignment is started by using the nominal shims. When necessary shims with another thickness are used to reach the criteria.

The final result of this alignment was:
Output beam:

Position	:	± 0.05 mm
Pupil co-alignment	:	± 65 μm
Direction	:	≤ 2.0 mrad
Co-alignment	:	1.4 mrad

As final check the total optical train was tested (both AFR's in tandem). It was found, that the co-alignment of the AFR's is within ± 0.25 mrad.

3.3 The alignment of the FIS

The alignment is determined to a large extent by the condition, that in a late stage detectors of the FIS can be changed. To meet this condition the design of the FIS is made modular. The various modules are:

- The main structure, that contains the mirrors. This structure consists of 2 parts, that are fitted together.
- A so called pedestal.
  This part is the interface between the detector module and the structure and contains reference ridges for the detector block. The dichroics are connected with the pedestals.
- The detector-lens assembly (DLA), that contains the detector module and the germanium lens. The DLA can be exchanged with help of the reference ridges (see figure 7). Therefore inside this assembly the detector is aligned very accurately with respect to reference ridges.

The set-up is schematically pictured in figure 6.
For the alignment auxiliary tools were used, like:

- An autocollimation theodolite, positioned at a distance of about 2 m. A video camera with monitor was coupled to the theodolite to make the adjustment/alignment handling with the theodolite more easy.
- A collimated He-Ne laser beam (λ = 633 nm, ϕ = 20 mm).
- A dummy detector-lens assembly (DLA). This aluminum block contains a glass reticle with concentric circles and a small cross in the center.
  This reticle is precisely aligned with respect to the reference ridges (accuracy < 5 μm).
- Two perspex mirror dummies with markings on the "mirror"side.
- Several flat mirrors for autocollimation.

The alignment of the FIS can be separated in 2 parts: the alignment of the pedestals with respect to the structure and the alignment of the (see figure) components.

Alignment of pedestals
This alignment is determined by a (reference) line through the center of the hole in the structure, where mirror (3) must be mounted. The center is determined by markings at the edge of the hole and can easily be determined with the theodolite focussed at the front surface. The direction of the line must be perpendicular to the back plane, which is determined also with the theodolite, used in autocollimation with a flat mirror in close contact with this backplane. In a fast iteration both conditions can be met (through center of hole and ⊥ back plane). The next step is using the dummy block with the reticle.
This block with reticle is adjusted in cross direction until the center of the reticle coincides with the line. Then the pedestal is fixed to the structure. In this way all 8 pedestals are aligned to the (still empty) structure of the FIS.

Alignment/adjustment of the optical components
This alignment is explained referring to figure 3. For the alignment the collimated laser beam is used. First the beam is directed perpendicular to a plane through 3 reference ridges at the entrance opening (control: autocollimation with plane parallel plate). The next step is the adjustment/alignment of the beam folding mirror (1) (criteria: beam in the center of opening (2), controlled with a reticle and beam perpendicular to back plane of opening (2), controlled by autocollimation). Adjustment of mirror (1) is performed by shimming and shifting in oversized holes. This process is started with nominal shims. After fixation of mirror (1) the parabolic mirror (2) is aligned and adjusted. Hereto the perspex dummy mirror with marks at the "mirror" side is mounted with nominal shims in hole (3). The perspex mirror with marks is centered in the hole using the theodolite. The reflected beam of mirror (2) is centered with respect to the marks on the perspex dummy mirror.

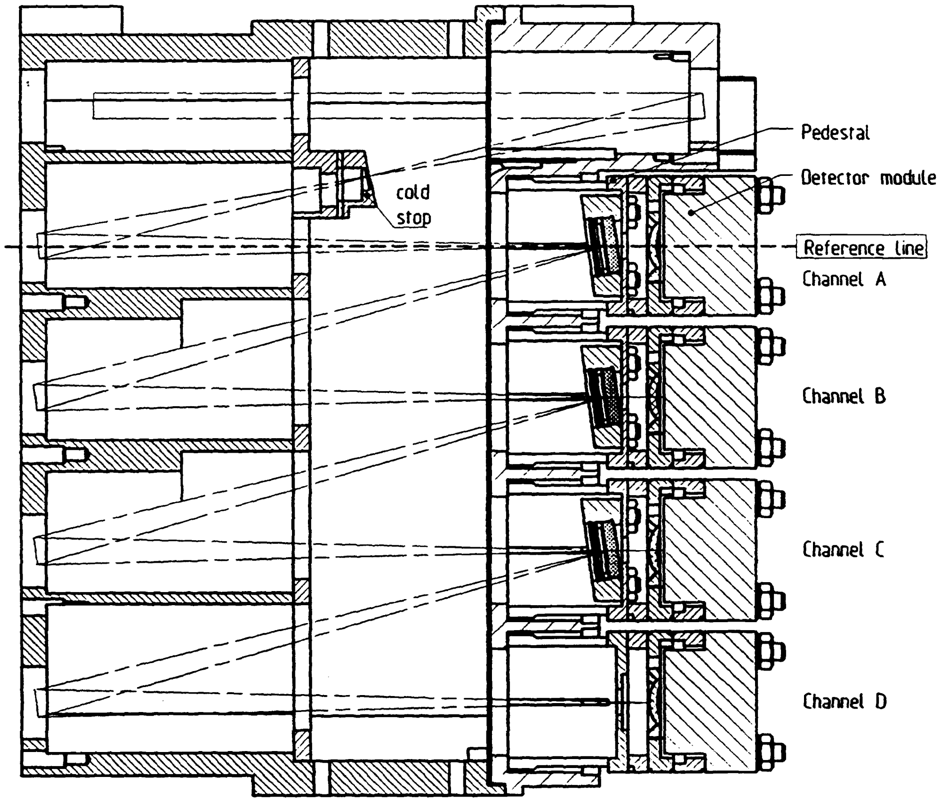

Figure 6 Alignment of the pedestals

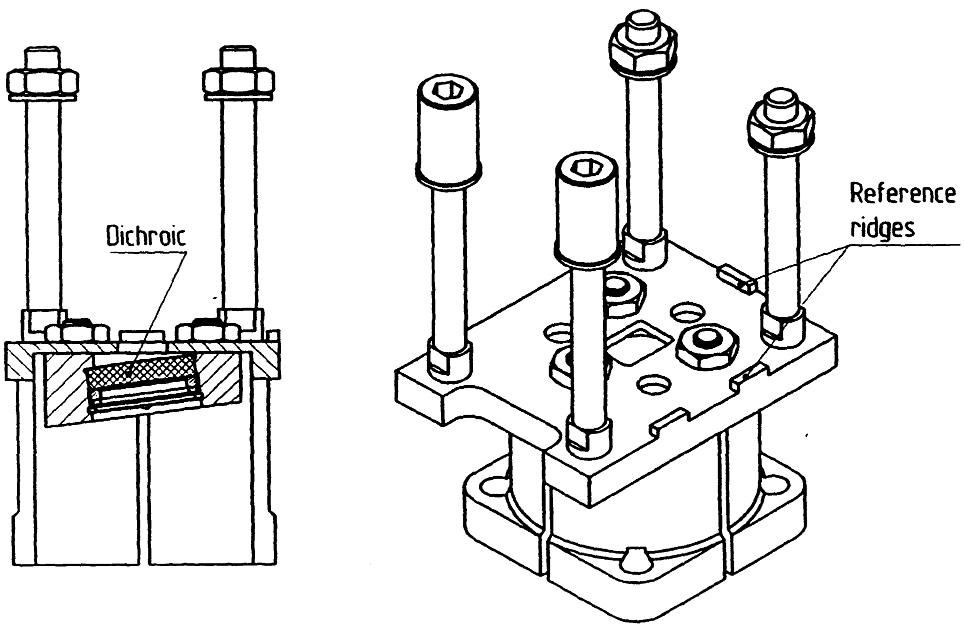

Figure 7 Pedestal

After fixation of mirror (2) the perspex dummy is removed and parabolic mirror (3) is mounted with nominal shims. Adjustment and alignment is performed until the reflected beam coincides with the center of the rectangular aperture of the pedestal. After fixation of mirror (3) of channel A the ZnSe dichroic (4) is mounted in the pedestal. The perspex dummy mirror is mounted and centered in the hole for mirror (3) of channel B with nominal shims. By oversized holes dichroic (4) of channel A can be shifted in cross direction until the center of the reflected beam coincides with the marks on the perspex mirror. This alignment procedure is repeated for the components of the other channels.

The final accuracy of the alignment was (including mechanical inaccuracy):

- Alignment of pedestals:
  Direction of reference line: ± 0.15 mrad
  Lateral position of reference line: ± 70 μm
- Alignment of entrance pupil:
  Lateral alignment: ± 25 μm.
  Direction of entrance beam: ± 0.3 mrad.
  Including strut interfaces the total accuracy at FIS axis alignment amounts: < 0.6 mrad.
- The lateral position of the image of the entrance pupil (at the position of mirror (3): ± 100 μm. This is at the detector plane: ± 4 μm.

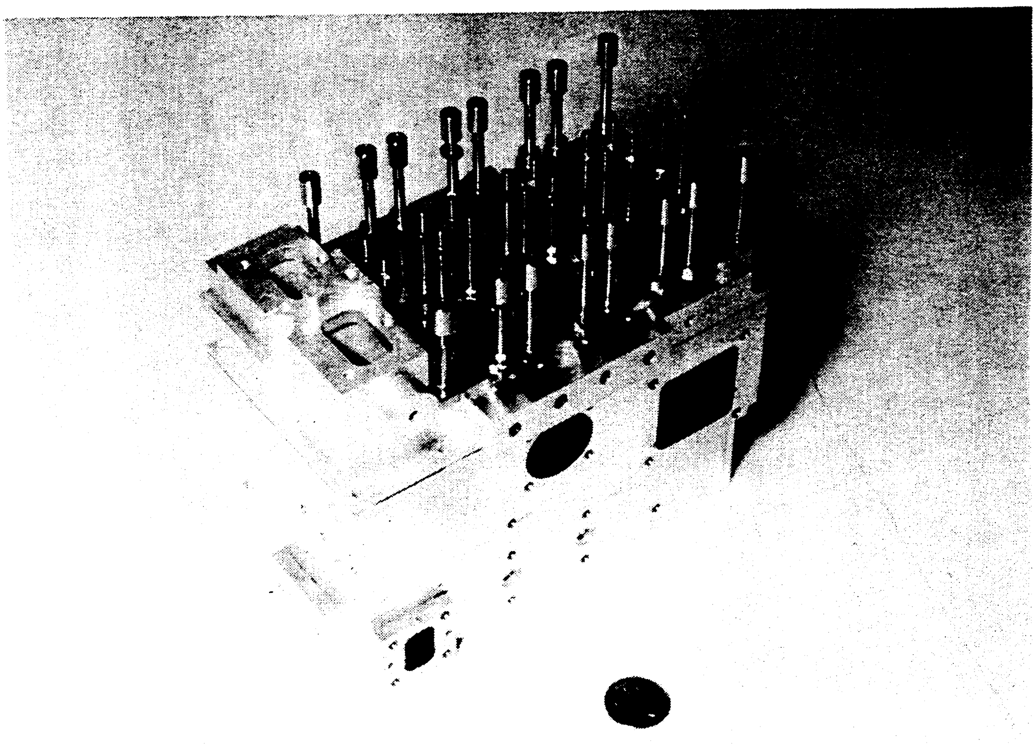

Figure 8 FIS hardware

4. CONCLUDING REMARKS

In this paper the design and the alignment of the focal plane system of MIPAS is described. Although the optical configuration is rather straightforward the final adjustment and alignment required some creative thinking. Especially the alignment of the pedestals, that was dictated by the replacement requirement of the detector module was not trivial.

Finally the adjustment/alignment of the AFR and FIS was performed within a period of 8 weeks, including a "learning" phase to find the optimal method. The result of these activities was satisfying by attaining a final accuracy within the specifications. It is expected, that the same procedure and equipment will be used for the alignment of the FM, that is planned in the second half of 1996.

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