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All reflective spectrometer design for Infrared Space Observatory

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Abstract

The European Space Agency ESA has started the development of the Infrared Space Observatory (ISO), that will be launched in 1993.
The TNO Institute of Applied Physics has been contracted for the major part of the optical/mechanical design of one of the 4 scientific instruments of ISO. This instrument, called the Short Wavelength Spectrometer (SWS) will measure stellar spectra in the wavelength range of 2.5 - 45 µm and will operate at a temperature of about 4K.
The severe performance requirements together with weight and space limitations made a special instrument design necessary, using an all reflective grating spectrometer configuration with excotic shaped aspherical mirrors.
At this moment the Qualification model of the SWS has been assembled and aligned and some optical, thermal and vibration tests have been performed with satisfying results.

1. INTRODUCTION

The Short Wavelength Spectrometer (SWS) is one of the four experiments of the Infrared Space Observatory (ISO) to be launched in 1993 as an Ariane payload.
The four scientific instruments are:

- ISOCAM , camera and polarimeter (3 - 17 µm)
- ISOPHOT, imaging photopolarimeter (3 - 200 µm)
- SWS , short wavelength spectrometer (2.5. - 45 µm)
- LWS , long wavelength spectrometer (45 - 180 µm).

The ISO satellite will have a 600 mm diameter liquid Helium cooled cassegrain telescope system and a Helium cooled Optical Support Structure (OSS) to which the four focal plane experiments are mounted (see figure 1). The focal length of the telescope system will be 9000 mm, resulting in an F/15 beam.

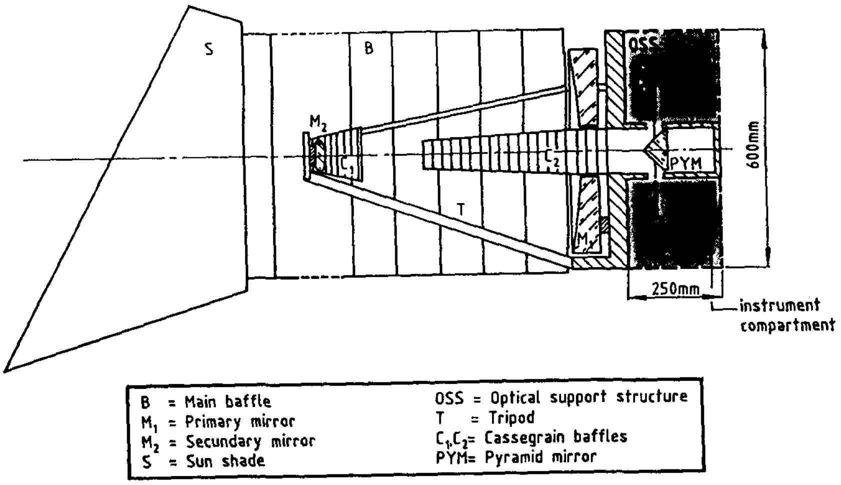


Fig. 1 ISO telescope and instrument section

Each of the four experiments, of which the SWS is one, occupies one quarter of the available dimensional envelope as given in figure 1. The instruments will operate at liquid Helium temperature (about 4 K).
The SWS experiment has been proposed to the European Space Agency (ESA) by a consortium of space research groups in the Netherlands and the Federal Republic of Germany.
The principal investigator of the SWS is Dr. Th. de Graauw of the laboratory for Space Research Groningen (ROG) in the Netherlands.
The TNO Institute of Applied Physics has been contracted by ROG for the major part of the optical/mechanical design and manufacturing.
The SWS has to measure stellar spectra in the wavelength range of 2.5 - 45 µm with a resolution of 10^3. For the wavelength range of 15 - 35 µm the resolution can be increased to 2 x 10^4 by means of two tunable Fabry-Perot filters.
To meet all the performance requirements, within the severe space and mass limitations, a rather complex optical system had to be designed, which will be described hereafter.

2. GENERAL SPECTROMETER CONCEPT

The main requirements of the SWS cryogenic instrument are:

- extremely large wavelength range (2.5 - 45 µm)
- wavelength resolution of $\geq 10^3$ for a spectrometer entrance slitwidth of 0.6 mm, corresponding to a field of view at the sky of 14 arcsec (0.9 mm or 20 arcsec for $\lambda >$ 30 µm, because of diffraction)
- two tunable Fabry-Perot filters to enhance the wavelength resolution to 2.10^4 over the 15 - 35 µm range
- limited space, no more than about 300 x 200 x 250 mm^3
- limited mass ($\leq$ 9 kg)
- operating at liquid helium temperature (4K)
- surviving launch conditions.

Different spectrometer concepts have been considered for the SWS such as:

- prism spectrometers
- first order grating spectrometers
- low order grating spectrometers, using grating orders 1 and 2 up to 3 or 4
- high order echelle type grating spectrometers.

The low order grating spectrometer concept has been selected because:

- prism spectrometers will not give the required resolution over the wavelength range
- first order grating spectrometers will need more than four gratings to cover the wavelength range and solve the grating order sorting problem, leading to serious space and mechanism problems.
- echelle type spectrometers need a cross-disperser to solve the echelle order sorting problem and generally have a somewhat lower efficiency. The complexity of the wavelength scanning, however, really kills this concept (mechanisms for echelle(s) and cross-disperser(s)). If large area, high efficiency, infrared image detectors would have been available the echelle concept is very attractive, because for image detectors the scanning mechanism problem may disappear.

To cover the wavelength range and solve the grating order problem in an acceptable way, we found that two gratings is the absolute minimum. We also found that it is more attractive to use two complete spectrometers with fixed gratings, than to use one optical lightpath in which one of two gratings can be selected. The two spectrometer concept opens the possibility to use dichroic beamsplitters at the spectrometer input, so that both spectrometers can be used simultaneously. Besides using two identical scanmechanisms is more attractive than a scanmechanism and a grating selecting mechanism.
To get the required wavelength resolution a beam dimension, in the spectral direction, of about 70 mm at the gratings is necessary. Because two spectrometers with 70 mm diameter circular beams will not fit in the available space, we have used exotically shaped aspherical mirrors to create beams with an elliptical cross-section (70 x 14 mm), that only have the necessary large dimension in the spectral direction. This approach, using aspherical mirrors, has also been followed to focus rectangular monochromatic images of the sky (7.5 arcsec x 20 arcsec) on to square detector elements (0.28 x 0.28 mm^2).

3. OPTICAL CONFIGURATION

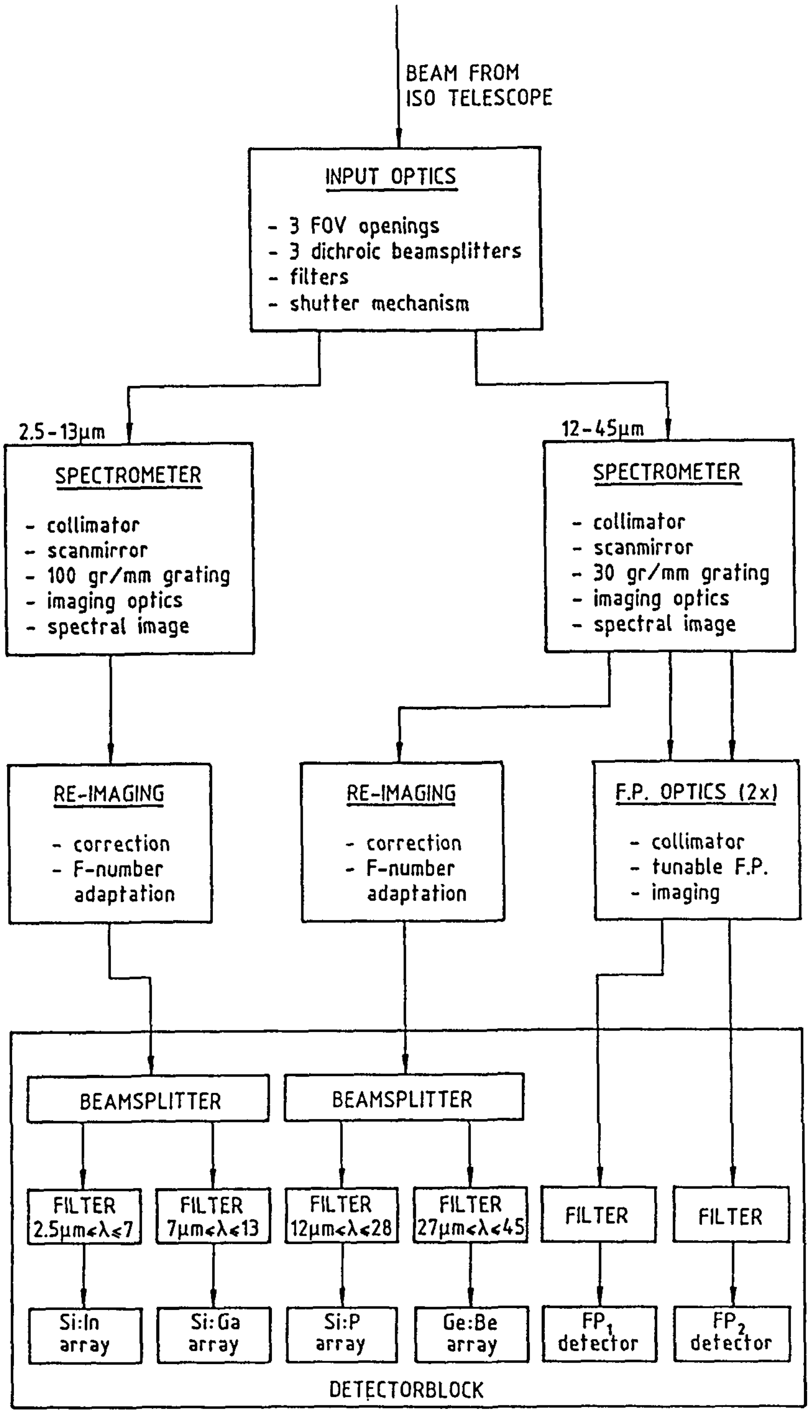


Fig. 2 Blockdiagram of the SWS

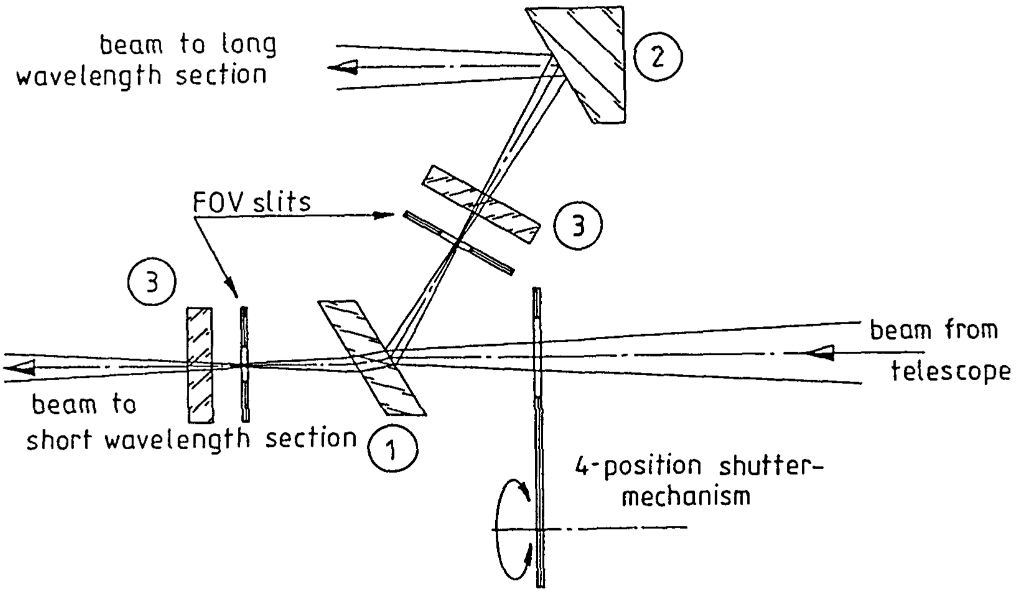
3.1. Blockdiagrams

In figure 2 a blockdiagram of the SWS is presented. Two basically identical reflection grating "SPECTROMETERS" together cover the entire wavelength range of 2.5 - 45 µm. The spectrometer of the short wavelength section covers the range of 2.5 - 13 µm. The spectrometer of the long wavelength section covers the range of 12 - 45 µm. In the detectorblock the spectral images of both spectrometers are spatially divided (after re-imaging) at the different detectors. The spectral image of the short wavelength section is directed to two 12 element detector arrays. The spectral image of the long wavelength section is directed to two other 12 element detector arrays and to two 2 element FP detectors (FP_1 and FP_2). The different optical blocks of figure 3 will be described briefly in the next subsections.

3.2. Input optics

The two spectrometers are coupled to the ISO telescope beam by the "INPUT OPTICS", in which one of three dichroic beamsplitter crystals is selected to direct certain wavelength bands to the spectrometers.

In figure 3 a schematic outline of the spectrometer input optical configuration is presented for one type of beamsplitter crystal (1). The complete input optical system consitsts of three times the optical system of figure 3 directly on top of each other perpendicular to the plane of the paper.
Only one of the three optical input systems can be used at a time. Selection is performed by a four position shutter mechanism.
The fourth position represents the shutter function. In this "closed" position no radiation from the telescope can enter the spectrometer sections of the SWS.



① Dichroic beamsplitter (3x) SrF_2 LiF Al_2O_3

② Reflection filter (3x)

③ Transmission filter position (6x)

Fig. 3 Schematic input optics

The reststrahlen reflection bands of the crystal materials SrF$_2$, LiF and Al_2O_3 together cover the entire wavelength range of the long wavelength section (12 - 45 μm).
The beamsplitter crystals are used in transmission for the short wavelength section (2.5 - 13 μm) and in reflection for the long wavelength section
(12 - 45μm).

As an example the reflection and transmission characteristics of a 3 mm thick SrF$_2$ crystal are presented in figure 4.
In the SWS the wavelength band of 27 - 45 μm is used in reflection, while the crystal material transmits from the visible up to about 13 μm.

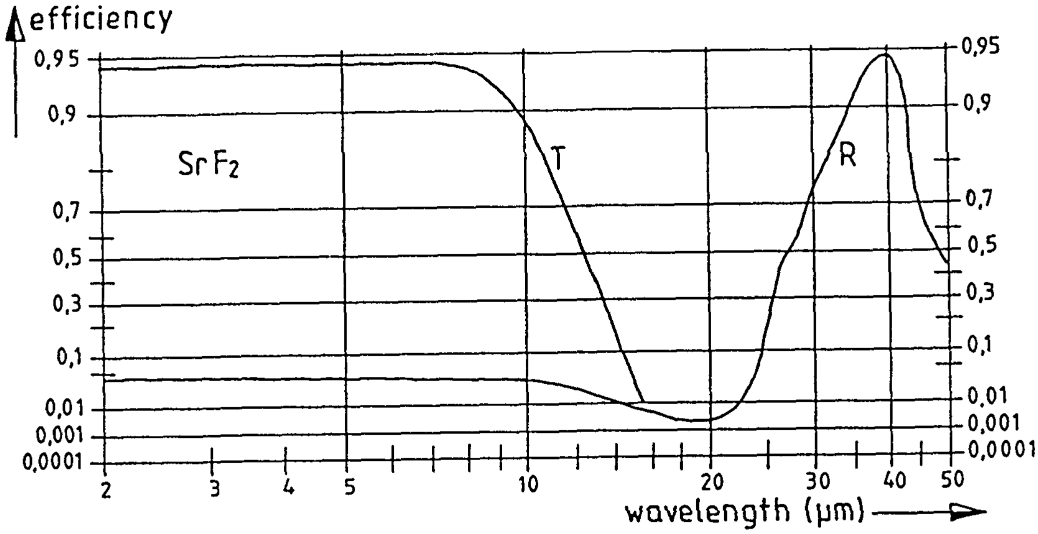


Fig. 4 Transmission (T) and surface reflection (R) of 3mm SrF$_2$

In the input optics the wavelength range of 2.5 - 45 μm is split up into six bands. The wavelength characteristics of these six bands are determined by the beamsplitter crystals (1), the transmission filters (3) and the reflection filters (2). The six bands are chosen such that the order problem of the grating spectrometers is solved (in combination with the wavelength characteristics of the detectors and filters in the detectorblock).

3.3. Spectrometers and re-imaging optics

In figure 5 an optical-mechanical drawing of the long wavelength section is presented. The divergent F/15 telescope beam, as transmitted through the spectrometer FOV slit (figure 3), is reflected into the plane of the spectrometer of figure 5 by the flat folding mirror (11).

Perpendicular to the plane of figure 5 the input beam is collimated to a parallel beam of 14 mm aperture by the saddle shaped toroidal mirror (12). In the plane of figure 5 the divergent F/15 beam is reflected as a more divergent beam (F/3.8) by the convex cross-section of mirror (12). At mirror (32) the beam is reflected as a fully collimated parallel beam of 70 x 14 mm (elliptical aperture).

The optical quality requirements for this beam can be met if mirror (32) is a parabolic cylinder (the cross-section in the plane of figure 5 is an off-axis part of a parabola and the cross-section perpendicular to figure 6 is a straigth line).

The collimated beam is directed to the flat scanmirror (33).
The scanangle of the scanmirror is ± 6.3 degrees, introducing an angular range of the incident beam at the grating of 25.2 degrees top-top. The measured diffracted beam is directed back from the 30 l/mm grating (34) to the scanmirror (33), to the parabolic cylinder (32) and to the toroidal mirror (12). A spectral image of the FOV opening is formed at the spectrometer exit slit (35).

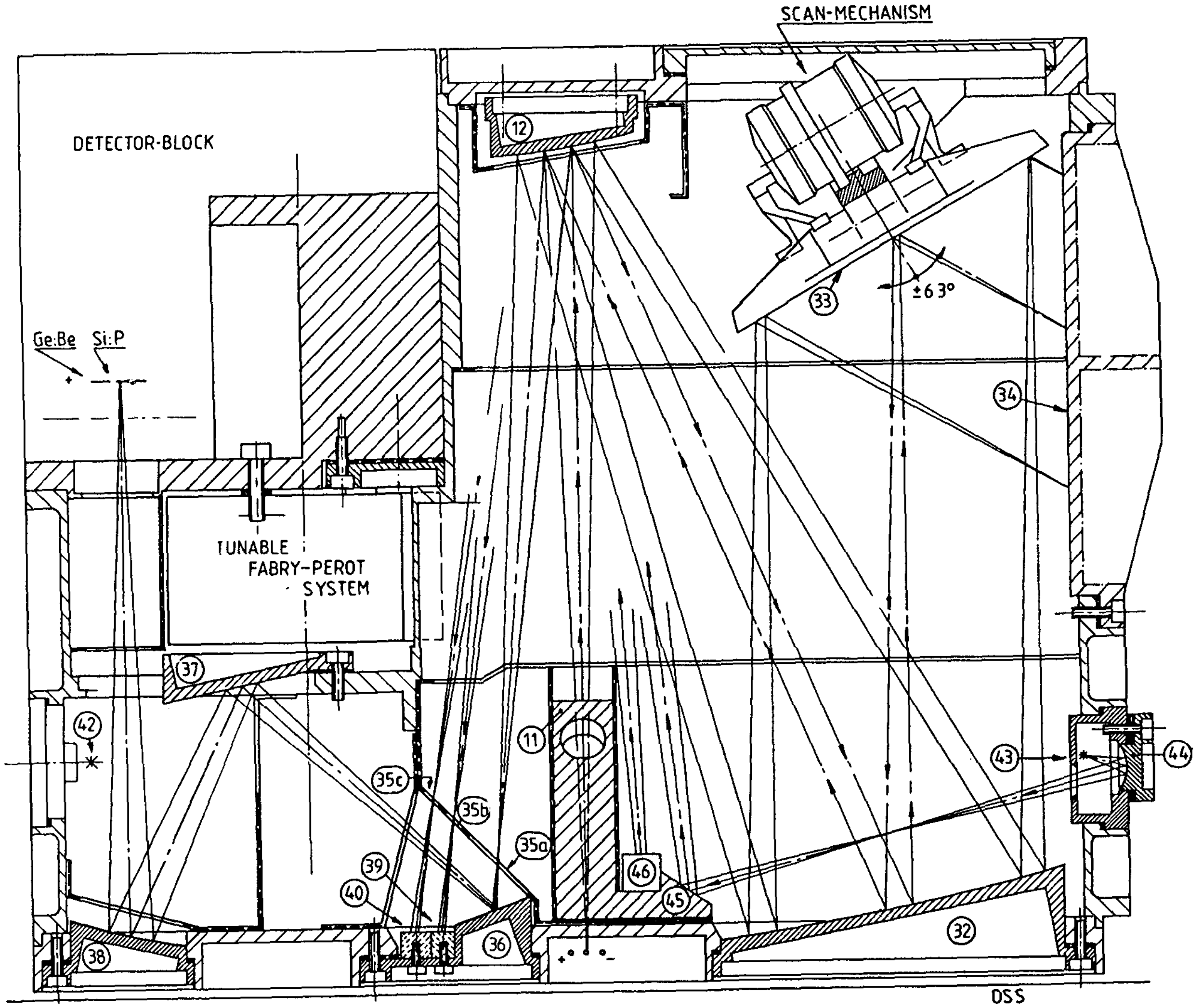


Figure 5 THE 12 – 45µm SPECTROMETER SECTION

The spectral image at the exit slit is very astigmatic, it does not have the required relative aperture for the detectors, it is not conveniently located for a detectorblock and straylight can be a problem at this position. For all these reasons the primary spectral image that is transmitted through the spectrometer exit slit (35a) is re-imaged by the mirrors (36), (37) and (38).
Mirror (36) is a concave cylindrical field mirror with a radius of curvature of about 300 mm in the plane of figure 5.
Mirror (37) has a conical shape. In the plane of figure 5 the cross-section of this mirror is straight line. Perpendicular to the plane of figure 5 the convex radius of curvature is about 26 mm average (varying over the mirror surface).

Mirror (38) re-images the spectral image and reflects the beam into the detector block. This toroidal mirror (38) has a concave radius of curvature of 164 mm in the plane of figure 5 and a concave radius of curvature of 104 mm perpendicular to the plane of figure 5. The spectral image inside the detector-block, formed by mirror (38), is (nearly) stigmatic and the relative aperture of the beam is adapted to square detectorelements. In the plane of figure 5 the relative aperture of the beam reflected by mirror (38) is F/13 and perpendicular to the plane of figure 5 the relative aperture of the beam is F/5.
For square detector elements of 0.28 x 0.28 mm^2 this results in a monochromatic field of view at the sky of about 7.5 arcsec in the spectral direction and about 20 arcsec perpendicular to the spectral direction. This (7.5" x 20") is the required monochromatic field of view per detector element at the sky for the Si:P detector array (12 elements). The Si:P detector array is used over the 12-28 µm wavelength range. Over the 27-45 µm wavelength range a 12 elements Ge:Be detector array is used.

As indicated in figure 5 there are two other parts of the spectrometer exitslit (35b) and (35c). The beams transmitted through these parts of the exit slit are reflected outside the plane of figure 5 by the flat folding mirrors (39) and (40). These two beams are directed to the Fabry-Perot system that will be described in section 3.4.

Indicated in figure 5 are also the calibration possibilities of the long wavelength section:
- a simple radiator (42) that directly and via reflections at the structure illuminates all the detectors of the short wavelength section of the detector block
- a more sophisticated source that consists of a radiator (43), a small concave mirror (44) and a flat folding mirror (45)
- a calibration beam, that is reflected from outside the plane of figure 5, over the flat reflector (46), into the plane of the long wavelength section. This beam is used to calibrate the Fabry-Perot system. The actual calibration source that generates the beam to reflector (46) will not be discussed in this paper.

The short wavelength section (2.5 - 13 µm spectrometer) is basically identical to the spectrometer of figure 5. The differences are:
- 100 l/mm grating instead of 30 l/mm
- no Fabry-Perot filters
- Si:In detector array (2.5 - 7 µm) and Si:Ga detector array (7 - 13 µm) of both 12 detector elements. The monochromatic field of view at the sky of all the short wavlength section detector elements is about 7.5" x 20".

3.4. Fabry-Perot optics

In figure 6 the lighpath over one of the two tunable Fabry-Perots is outlined, starting at the F.P. part (35c) of the exit slit of the long wavelength section. For presentation purposes this lightpath is rotated over some of its mirrors in such a way that the principle ray of the entire lightpath is shown in the plane of figure 6. Better information on how the components of the FP optics are spatially orientated with respect to each other will be presented in figure 7 of section 3.5.

Following the lightpath of figure 5 the astigmatic beam, coming from the saddle shaped toroidal mirror (12), is transmitted through the spectrometer exit slit (35c) and directed to the two flat folding mirrors (40) and (47).
This divergent beam is collimated to a parallel beam with a (nearly) circular diameter of 27 mm by the telescope system that is formed by the convex toroidal mirror (48) and the off-axis ellipsoidal mirror (49).

In the tunable Fabry-Perot the collimated beam will increase in diameter to the aperture of the Fabry-Perot (35 mm). This parallel beam of 35 mm diameter is focussed on the FP-detector by a mirror system that consists of a off axis ellipsoidal mirror (50) and a convex spherical mirror (51).
A similar lightpath as shown in figure 6 can be outlined for the other tunable Fabry-Perot. This second tunable Fabry-Perot is coupled to the other FP-opening (35b) of the exit slit of the long wavelength section. Because this outline would be almost identical to figure 6, it is not presented here.
The two tunable FP-filters together cover the wavelength range of about 15 - 35 µm, giving a wavelength resolution of about 2 x 10^4. The actual FP-filters are formed by open metal meshes.

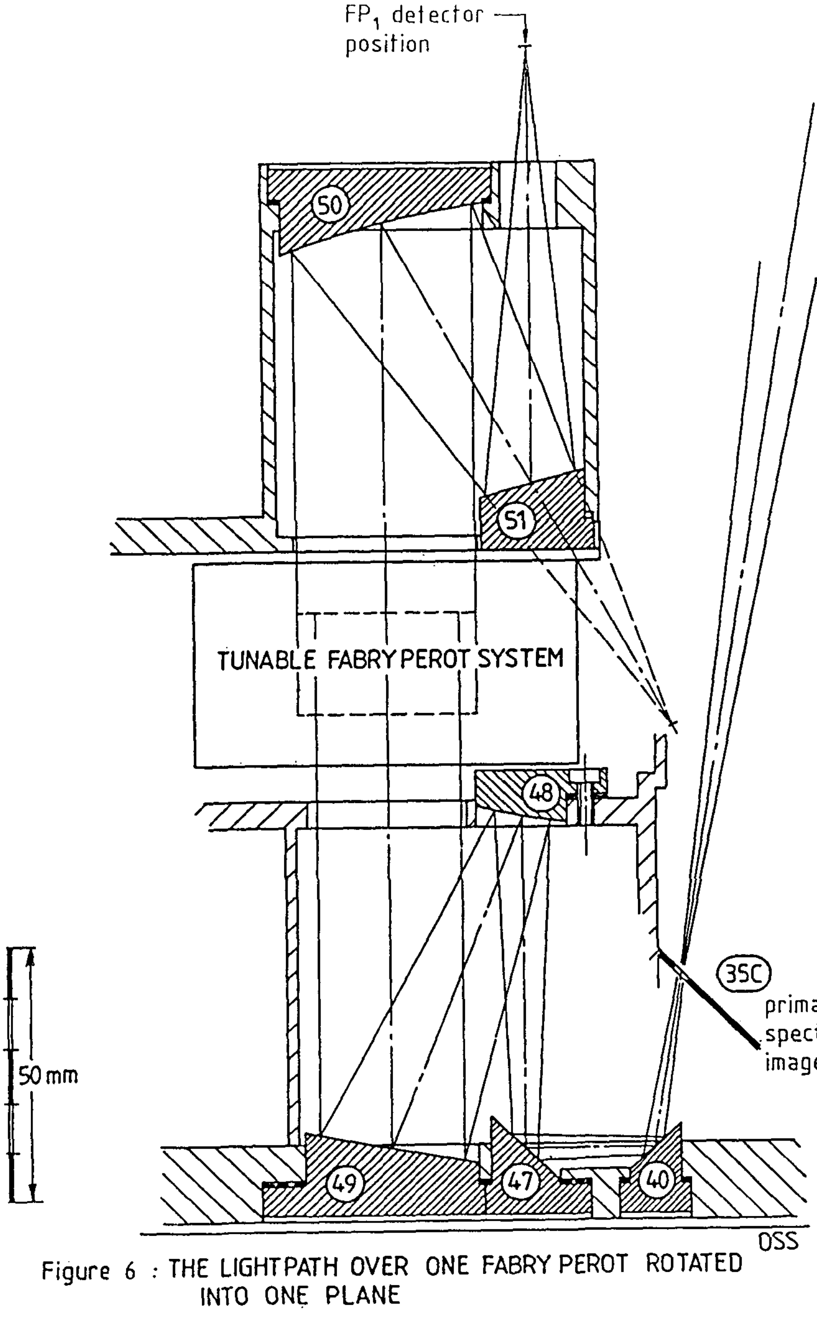


Figure 6 : THE LIGHTPATH OVER ONE FABRY PEROT ROTATED INTO ONE PLANE

3.5. Dimetric view

In figure 7 a dimetric overall view of the SWS optics is presented. The same numbers of the optical elements as in the figure 5 and 6 are used in figure 7, so that without further explanation the compact concept of the SWS optical configuration can be understood.

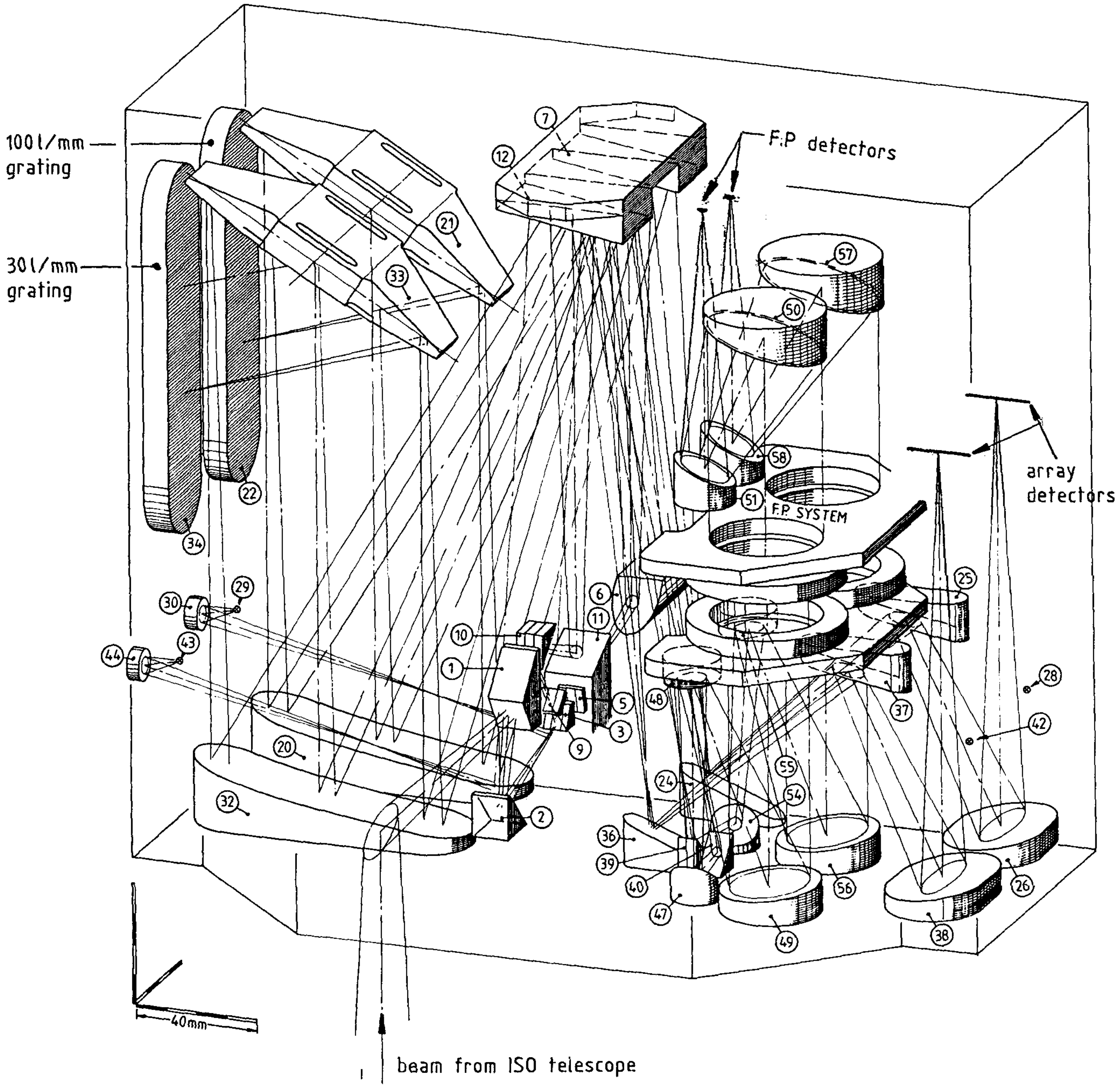


Fig. 7 Dimetric view of SWS optics

4. WAVELENGTH RESOLUTION

The calculated wavelength resolution for the near littrow grating spectrometer configuration, as described in section 3, is presented in figure 8. For this calculation extended infrared sources are assumed. The calculations are corrected for diffraction effects.

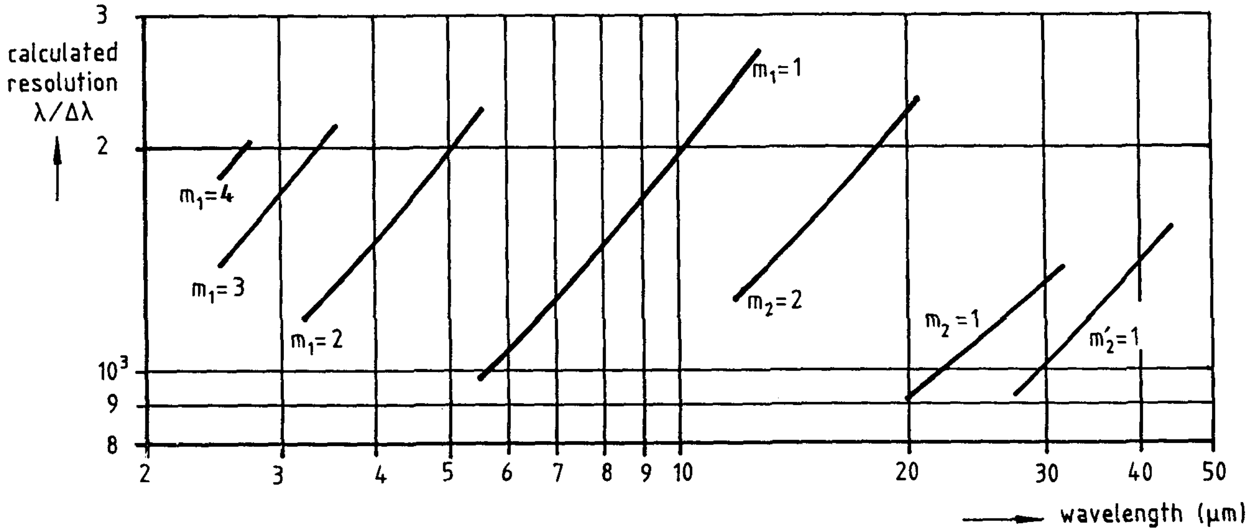


Fig. 8 Calculated wavelength resolution of the SWS for extended infrared sources, diffraction included

m_1 = 1 : 1st order 100l/mm grating, 5.5 - 13 µm
m_1 = 2 : 2nd order 100l/mm grating, 3.3 - 5.6 µm
m_1 = 3 : 3rd order 100l/mm grating, 2.5 - 3.6 µm
m_1 = 4 : 4th order 100l/mm grating, 2.5 - 2.7 µm
m'_2 = 1 : 1st order 30l/mm grating, 27 - 45 µm
m_2 = 1 : 1st order 30l/mm grating, 20 - 32 µm
m_2 = 2 : 2nd order 30l/mm grating, 12 - 21 µm

For all wavelength ranges, except the m'_2 range (27 - 45 µm), the spectrometer entrance slitwidths correspond to 14 arcsec. at the sky. To avoid serious diffraction problems the m'_2 range has a 20 arcsec slitwidth. At the position of the slits in the focal plane of the ISO telescope, this corresponds to slitwidths of 0.6 mm (14") and 0.9 mm (20").

5. MECHANICAL CONFIGURATION

5.1. General design considerations

To obtain good thermal properties and intrinsic mechanical stability the mechanical design of the SWS has the following main characteristics:

- mirrors and gratings from the same material as the mechanical structure (aluminium alloy 6082)
- large, complex main mechanical structure, machined out of one piece of aluminium, to which smaller components (also alloy 6082) are mounted
- flexible mounting of the SWS to the satellite by one rigid and two flexible fixation feet.

5.2. Mechanical design of the optical components

Apart from some small filters and beamsplitters the entire optical system of the SWS consist of two reflection gratings and a large number of mirrors. All these optical surfaces are manufactured, from aluminium blanks (alloy 6082). Mounting of the optical components in the mechanical structure of the SWS is simply accomplished by three holes for M3 fixation screws in the blanks of the optical components.

An example of a mechanical design of a mirror, as presented by our CAD system, is given in figure 9.

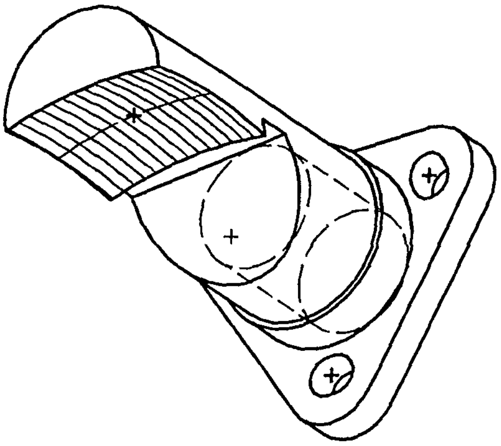


Fig. 9 Mechanical design of (toroidal) mirror

The optical surfaces of the mirrors have been diamond cut directly in the aluminium mirror blanks. By this method mirrors with a surface figure better than one visible wavelength and a surface roughness better than 15 nm have been obtained. Only the two large parabolic cylinders (components (20) and (32) in the figures 5 and 7) could not be manufactured by diamond turning. They have been manufactured by conventional polishing in kanigen coated aluminium blanks.

The gratings are original rulings in coated aluminium blanks.

All metal mirrors and gratings have been gold coated (200 nm thick) to enhance the reflectivity.

The thermal properties of the mirrors and gratings are such that they have proven to survive direct immersion from room temperature in liquid nitrogen.

5.3. Mechanical structure

As mentioned in section 5.1. the mechanical structure of the SWS consists of one large complex component out of aluminium alloy 6082, to which smaller functional components (like mirrors, gratings, mechanisms, detectorblock, top cover and bottom cover with mirrors) are mounted. In figure 10 a CAD presentation of two views of the main mechanical structure is given. The dimensions (L * D * H) of this structure are about 280 x 180 x 235 mm^3.
All the functional components of the SWS are mounted and adjusted (by shims) from the outside of this structure.

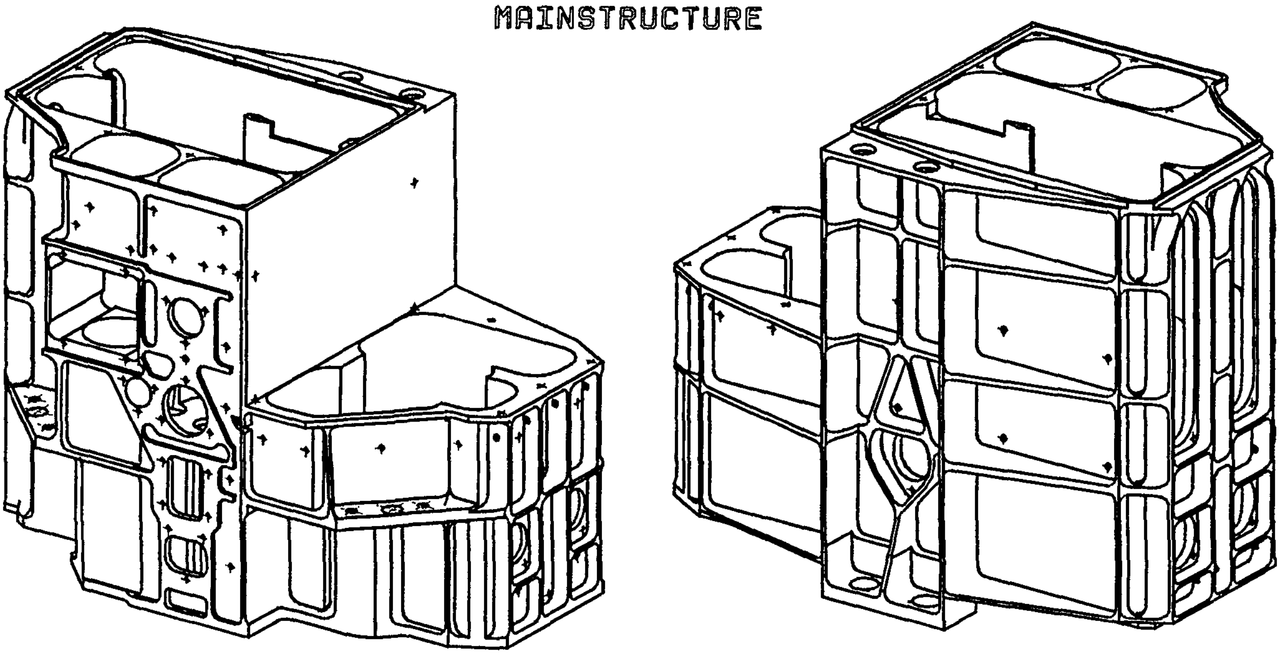


Fig. 10 Main structure of SWS
(CAD presentation)

6. ALIGNMENT AND TESTING

The Qualification model of the SWS has been assembled, aligned and subjected to some tests. This QM contained all components as described except for the detectorblock, the final scanning mechanism and the Fabry-Perot filters.
A photograph of the complete SWS is given in fig. 11. In fig. 12 the bottom cover part with its mirrors is shown.
The following measurements/tests have been performed:

- Optical quality
  The alignment and determination of the optical quality have been performed in the visible, using a He-Ne laser at $\lambda = 633$ nm.
  The measured image quality (90% energy) at the detector plane is better than the dimension of one detector element.

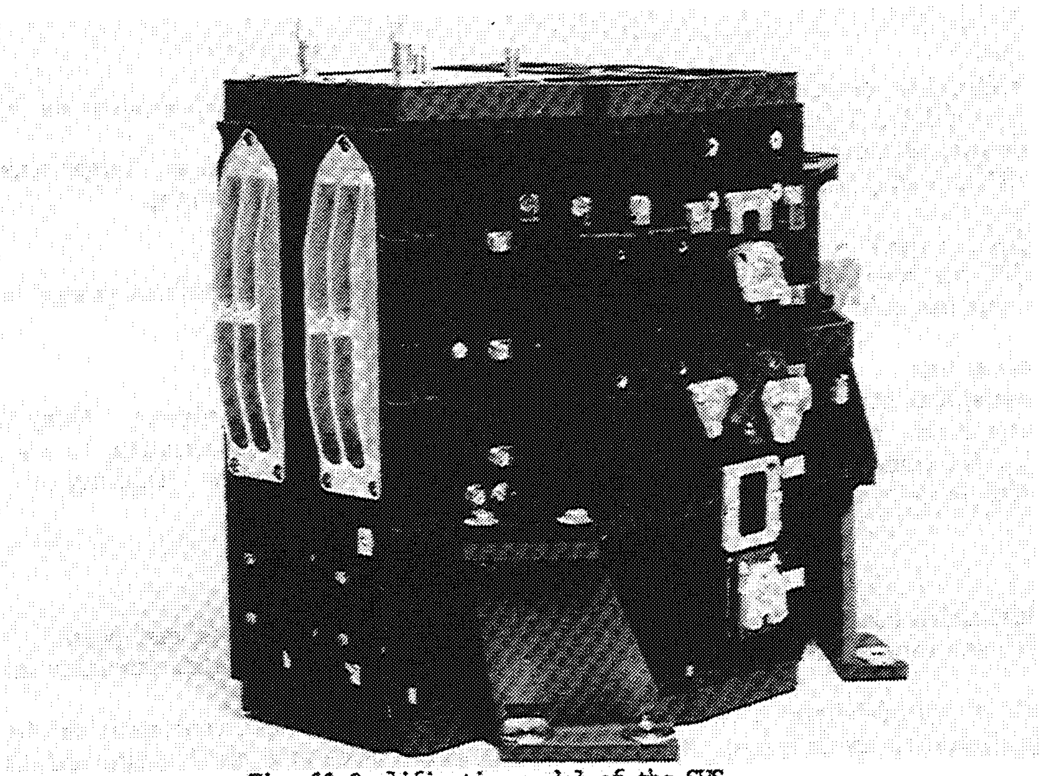


Fig. 11 Qualification model of the SWS

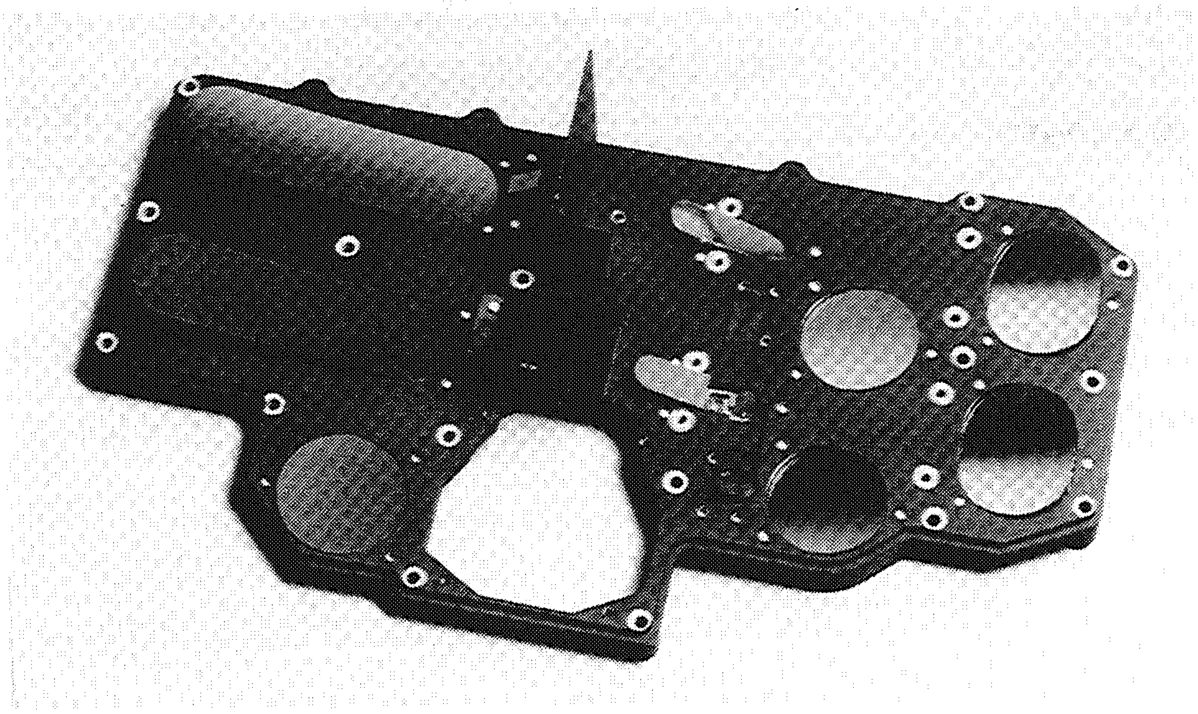


Fig. 12 Bottom cover of the SWS with mounted mirrors

- Efficiency
  The reflection efficiency of some lightpaths in the SWS-QM has been measured for a wavelength of 0.633 µm and 1.523 µm.
  The overall efficiency appeared to be satisfactory, considering that at larger wavelength, where the SWS is really used this efficiency increases due to reduced scattering.

- Temperature check
  The SWS has been cooled down to about 130K. As expected no significant change in alignment or focussing has been found.

- Vibration test
  The mechanical structure, including mass dummies for components like mirrors, Fabry-Perot filters, detector block and mechanisms has been subjected to vibration tests according to ESA qualification levels. All components have survived the tests. The lowest resonance frequency of the structure appeared to be > 300 Hz.

7. CONCLUDING REMARKS

The Qualification Model of the SWS instrument for ISO is in its integrated test phase.
The first test results concerning optical quality and thermal and mechanical stability are satisfactory.
The result of this development is a complex all mirror spectroscopic configuration for an extended wavelength range in the infrared, that combines high performance with small weight and dimensions.
With this development it has been proven, that due to advanced manufacturing techniques of accurate aspherical metal mirrors new spectrometric possibilities, especially for the infrared, have become possible.

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