IASI OGSE Spot Scan: Design and realization of an infrared test equipment for use in vacuum

J.P. Kappelhof*, B. Dekker, H. Spierdijk, E. Boslooper, H. Bokhove, P. Verhoeff

TNO TPD, Delft, the Netherlands

ABSTRACT

This paper presents the development of the IASI Infrared Spot Scan test equipment, with a focus on the mechanical design. The IASI instrument, developed by Alcatel, is a spaceborne meteorological instrument, for observation of the Earth atmosphere in the infrared wavelength region. An infrared Optical Ground Support Equipment (OGSE), developed by TNO TPD is used to test the focal plane of the IASI instrument. The characterization is done by response measurement of an infrared spot scanning the detector area of IASI. The vacuum part of the OGSE consists of 3 linear stages, an optical table comprising an infrared source, an elliptical mirror, a shutter and a diaphragm. The system is partly cooled. A control system for stages, shutter and thermal control completes the system.

Keywords: Ground Support Equipment, vacuum, opto-mechanics, infrared, cryogenic, scan system, shutter, iso-static design, active thermal control

1. THE IASI MISSION

The Infrared Atmospheric Sounding Interferometer (IASI) is a spaceborne instrument designed to measure the temperature and humidity distribution of the atmosphere. This is done by spectrometry in the infrared from 3.6 µm to 15.5 µm. The instrument will be flown as part of the payload of the Meteorological Observation Platforms (METOP) series, operated by the EUropean organisation for METeorological SATelites (EUMETSAT). These satellites will be used for meteorological and atmospheric research purposes. The IASI instrument (Figure 1) is developed by ALCATEL Space in France. TNO TPD has developed the IASI Spot Scan Optical Ground Support Equipment (IASI Spotscan OGSE), which will be used to perform tests on the cold focal plane assembly or Cold Box System (CBS; optics and detectors). The project has been carried out in collaboration with Dutch Space.

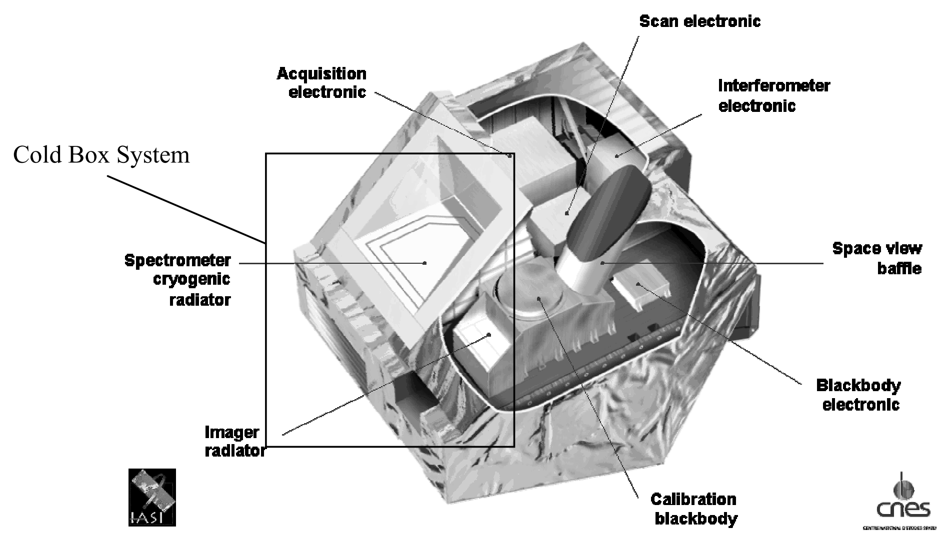

Figure 1: The IASI instrument.

* kappelhof@tpd.tno.nl; phone ++31 15 26 92095; fax ++31 15 26 92111; www.tpd.tno.nl

2. THE IASI OGSE SPOT SCAN

The IASI OGSE Spot Scan has to test the detector module inside the Cold Box System (CBS) in the IASI instrument (see Figure1). Therefore two types of tests have to be performed in a vacuum environment.

- Cold Box Field Response (CBFR test): determines the field response of the IASI instrument pixels (see Figure 2). To this end, the 8 mm diameter pixels are stimulated with a well-defined (flux and position) 0.8 mm diameter IR "point" source, which is provided by the Spot Scan. This point source is scanned line by line over the Cold Box field stop, which defines the 4 IASI pixels. The 2 mm/s scanning is performed by S/W controlled vacuum compatible translation stages, yielding absolute position knowledge accuracy for the spot of 50 micrometer during scanning.
- Cross Talk test (CT test): a high-speed shutter is employed to illuminate a full pixel, while at the same time the response of the other pixels is measured.

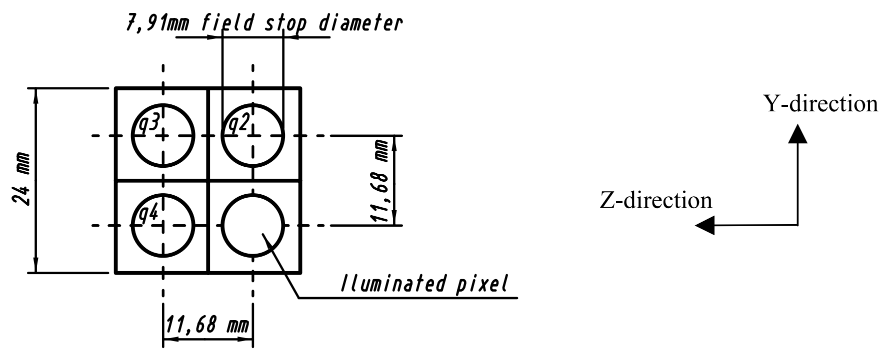

Figure 2: The four pixels inside the CBS of the IASI instrument (as illuminated in the cross talk test)

The main performance characteristics for the IASI Spot scan OGSE are summarized below:

- Spotsizes: 0.8 mm diameter for CBFR test and 9 mm diameter for CT test
- CBFR spot flux density, in IASI spectral bands and corresponding Black Body (BB, the infrared source) temperatures:

band	*Wavelength range*	*BB temp.*	*Flux density*	*BB temp.*	*Flux density*
B1	8.4 – 15.5 µm	670 K	10 μW		
B2	5.0 – 8.4 µm	670 K	16 μW	478 K	4 μW
B3	3.6 – 5.0 µm			478 K	1.4 µW

Table 1: Spectral bands of IASI OGSE Spot Scan.

- Low (100 nW/pixel in band B3) and stable background radiant flux
- XYZ translation capability:
  - YZ spot positioning accuracy better than 20 µm
  - Focusing accuracy, along the X-axis, better than 50 µm
  - 2 mm/s scan along the Z-axis
- CT test shutter opening time selectable in the range 9 – 151 ms
- High thermo-mechanical stability (< 20 µm) during a complete (4 pixel) CBFR scan test (about 45 minutes)
- Better than 50 µm spot position knowledge during Z-scan
- System synchronisation with IASI data acquisition
- Remote alignment provision in the visible light
- Under vacuum operation
- The height of the overall system is approximately 1.7 m, weight about 350 kg

3. DESIGN DESCRIPTION

1. Overview

The overall Spotscan system consists of the following two main assemblies and the harness in between:

- OUVE: OGSE Under Vacuum Equipment
- OCE: OGSE Control Equipment (incl. control computer and S/W)

This paper focuses on the OUVE design, with a focus on the mechanical aspects. An overview of the OUVE is given in Figure 3. It consists of the following main assemblies:

- Optical table assembly
- XYZ translation system assembly
- Support box assembly

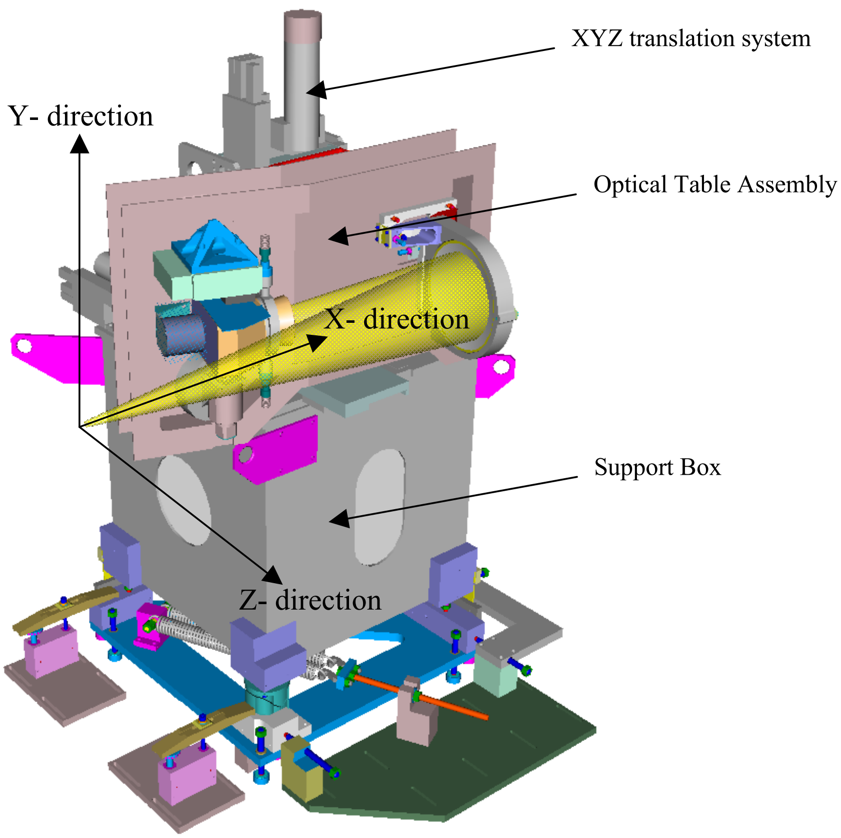

Figure 3: IASI OGSE Spot Scan assembly (OUVE)

2. Optical Table Assembly

Overall design

Figure 4 presents the lay out of the optical design of the Spot scan. The optical design is based on a spot, which is imaged onto the CBS pixels by means of an (elliptical) relay mirror. The CBFR diaphragm is actually a pinhole in a moveable cooled aluminium plate (cooled diaphragm). Apart from the CBFR diaphragm, this cooled plate contains the CT diaphragm and a mirror (not shown) looking downward under an angle of 45 º to a CCD camera for remote visual alignment. The baffle and the diaphragm are painted black, to achieve sufficient homogeneity of the cold area. To enable selection of the different diaphragms or the visualisation system, the cooled plate is mounted onto a linear stage, which in its turn is mounted onto the optical table. The Black Body, a heated graphite cavity, is mounted behind the diaphragm. Since the spot flux density on the CBS pixels, in the OGSE focal plane, depends on the BB temperature the BB is closed loop temperature controlled and can be heated up to a maximum temperature of 720 K. The required flux densities are such that they cannot be met for a single BB temperature: for 670 K the band 1 & 2 and for 478 K the band 2 & 3 flux densities are within the specified range. To ensure a low background radiant flux, the diaphragm is cooled to 90 K. A baffle and a shroud enclosing the diaphragm are cooled to 120 K.
Finally, the shutter, required for the CT test, is mounted between the BB and the diaphragm plate.

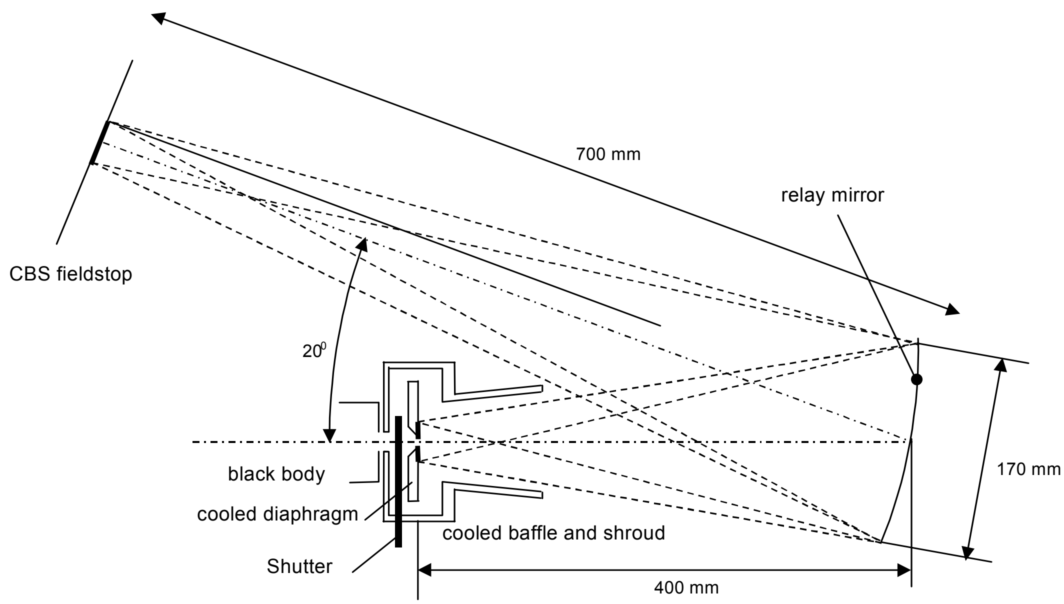

Figure 4: Overview of the IASI OGSE Spot Scan optical configuration

The optical table is subject to several mechanical design constraints. Firstly, due to the limited load capacity of the XYZ translation system the overall weight of the table and its components had to be less than 25 kg. Secondly, as in the final test set-up at Alcatel, the radiometric OGSE is located next to the spotscan OGSE, envelope constraints set by the customer have to be taken into account, requiring a compact design. Thirdly, the thermo-mechanical loads introduced by the cold LN_2 cooling system and the hot Black Body in the optical table. Special measures are needed to achieve the required spot position stability.

Optical table
The optical table itself is a lightweight Aluminium table of 4.5 kg (see Figure 5). In order to achieve optimal thermal and dynamic stability, the table is a one-piece aluminium component. The table has a symmetric U shaped edge all around. This edge avoids bending of the table due to a-symmetrical thermal gradients while adding sufficient stiffness for dynamic stability (see Figure 6).

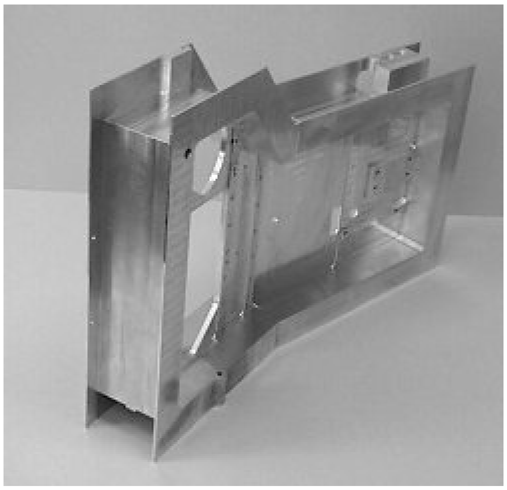

Figure 5: One-piece aluminium table.

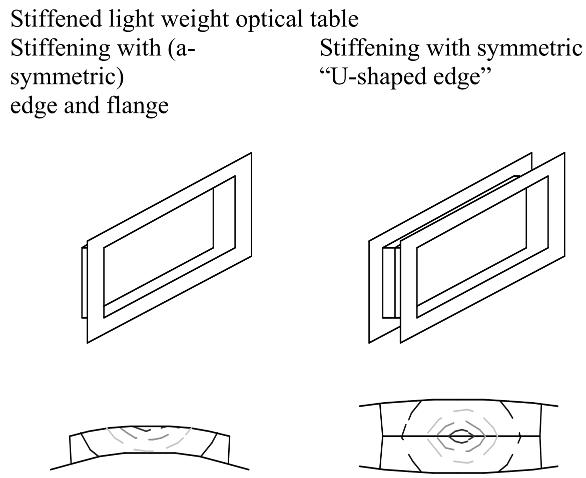

Figure 6: Improved thermo-mechanical stability due to table with U-shaped edge

Relay mirror
The gold-coated elliptical mirror can be aligned over 2 rotational degrees of freedom and one translational degree of freedom. Rotational alignments are realised by a cardanic flexural joint. Locking devices ensure proper fixation after final alignment (see Figure 7).

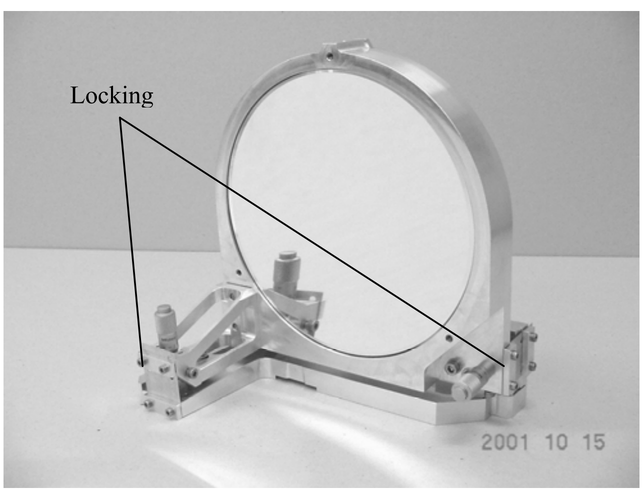

Figure 7: Elliptical relay mirror and alignment devices.

Diaphragm plate

Figure 8 shows the diaphragm plate (during the integration phase). This plate is mounted on a linear stage to enable selection of the different diaphragms (CBFR, CT) or the visual alignment positions. The diaphragm is suspended by an isostatic support, consisting of 6 Titanium Aluminium Vanadium alloy (TiAlV) struts. TiAlV is used for low thermal conductivity to insulate the LN_2 cooled diaphragm (90K) from the stage, which is at room temperature. The struts realize a nearly stress-free suspension. The transition from the (high conductivity) aluminium diaphragm plate to the steel LN_2 tubes is implemented via two "bimetallic junctions". After these junctions flexible bellows are welded in between the junction and the stainless steel tubes. This part of the tube is mounted to the diaphragm plate bracket by means of Polyimide rings to realise proper thermal isolation. The lowest eigenfrequency of this system is 108 Hz.

Baffle and shroud

The diaphragm plate (Figure 8) is thermally insulated from the (room temperature) environment by the cooled shroud. At the front a baffle is integrated on the shroud. The baffle and shroud, made of high thermal conductivity Al 2200 (nearly pure Aluminium), are LN_2 cooled to about 120 K. Due to a proper annealing treatment a very homogeneous material structure is realised. The baffle and shroud (Figure 9), made of one piece, are painted black at the inside and Multi Layer Insulation (MLI) covered on the outside. A hollow ring is welded around the baffle. At the top and the bottom of this ring two "bi-metallic junctions" are welded to mount the stainless steel cooling tubes in the baffle and shroud. The shroud is mounted on the optical table by insulating supports (stainless steel blades and Polyimide rings).

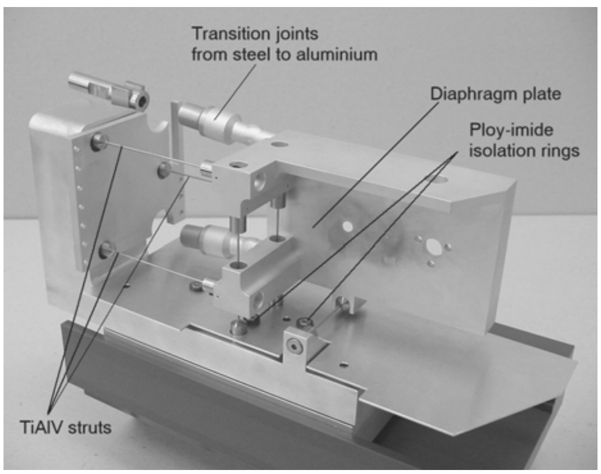

Figure 8: Diaphragm plate.

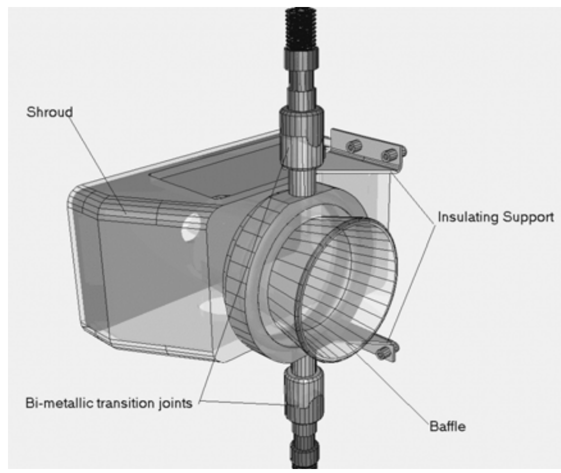

Figure 9: Baffle and shroud.

Shutter

For the Cross Talk test, a selected pixel is completely illuminated for (a series of) very short exposures. The exposure time is selectable between 10 ms and 150 ms, implemented via a shutter between diaphragm and BB. The shutter vane is mounted in between cooled shroud and diaphragm. In this way the shutter will be cooled as well. The shutter mechanism consists of an aluminium vane (good conduction) mounted on a TiAlV flexural hinge. The vane is actuated by a coil, which is guided by a shaft sliding through a ceramic bush lubricated by vacuum compatible grease. The control of the shutter is open loop. First a force is applied to open the shutter. To minimise impact at the end stops a force is applied to decelerate the shutter again. A small force is applied to keep the shutter in open position. To close the shutter the cycle is applied in reverse order. See Figures 10 and 11.

Visualisation system

Below the diaphragm and stage the visualisation system (VIS System) is mounted. This system is used to be able to look through the system in visible light, and thus to enable remote alignment of the Spot Scan with respect to the CBS pixels. The system consists of a small lamp and a non-vacuum compatible standard CCD camera, mounted in a pressurized container with a window.

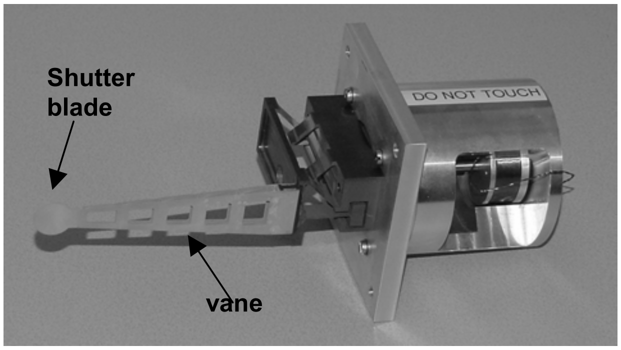

Figure 10: The shutter mechanism

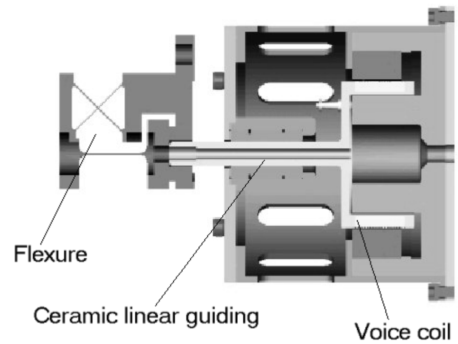

Figure 11: Section of the actuator module of the shutter mechanism.

3. XYZ translation system

The orthogonally stacked linear X,Y, Z stages are procurements from Anorad USA (Figure 12). The lower Z-stage, perpendicular to the optical axis, is used for scanning. Additionally, it is used to switch between the Spot Scan OGSE parking, enabling IASI tests with the radiometric OGSE, and the working positions (for Spot Scan OGSE tests). The total stroke of the Z-stage is about 400mm, where only ± 30 mm is used for scanning. The X-stage, parallel with the optical axis, is used for focusing the system. On the vertical Y-stage the optical table is mounted. A spring-lever weight compensation has been added to reduce the (static) motor torque and thus the thermo-mechanical load on the optical table.

The commercial stages are made vacuum-compatible by, amongst others:

- modification of the coil wiring
- use of vacuum compatible lubrication (Fomblin oil)

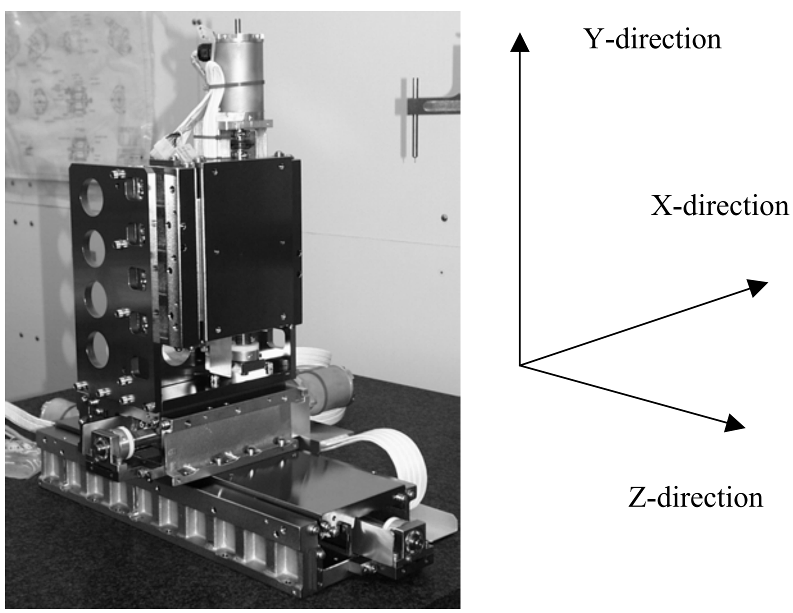

Figure 12: Three orthogonal stacked linear stages.

4. Support Box

The support consists of a triangular box made of stainless steel plate (the same material as the base plate the system will be mounted on at Alcatel) and an alignment system in between box and vacuum chamber optical bench (base plate). This system can realise a coarse alignment in 4 degrees of freedom (resolution: approx. 0.5 mm and 0.5 degree). For coarse alignment the system is placed on three (vertical) screws by which the system can be lifted. The screws rest on three PTFE pads. Due to the low friction coefficient the system can slide in the horizontal plane. When coarse alignment is finalised, the instrument is clamped to the Alcatel breadboard. Fine alignment is done by rotation of the whole box relative to the IASI instrument around the horizontal X and Z-axes (resolution approximately 1 microrad.) This alignment is performed by means of a cardanic flexural hinge in combination with 2 fine threaded screws. Locking devices are implemented to guarantee stable positioning during several months of operation.

5. Thermo-mechanical design aspects

LN_2 cooling system

The cooling of the diaphragm and baffle and shroud is performed via a liquid nitrogen flow through the aluminium components. The LN_2 enters the baffle and shroud and the diaphragm at the bottom side. After cooling both systems the liquid/gas mixture flushes to the top of the instrument, where a gas/liquid separation vessel is situated. The gas is released via the return channel. Standardised flexible stainless steel is used. These tubes are guided in different loops to be able to cope with the movement of the 3 linear translation stages as shown in Figure 13.

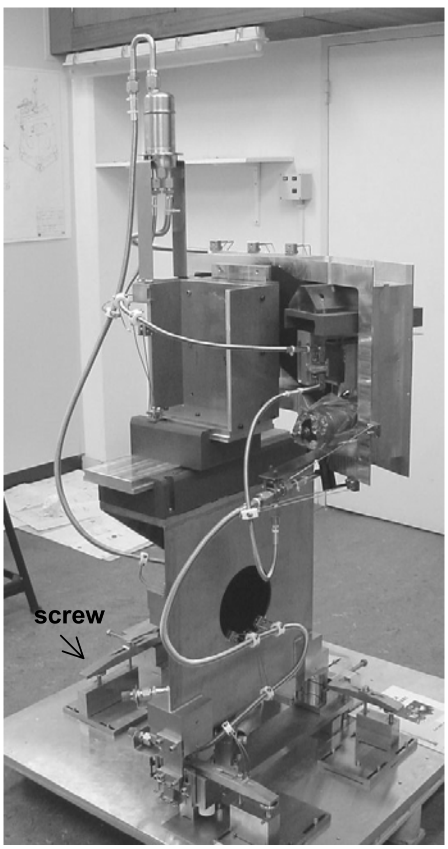

Figure 13: Stainless steel tubes in different loops to cope with motion of the stages. Photograph taken during integration.

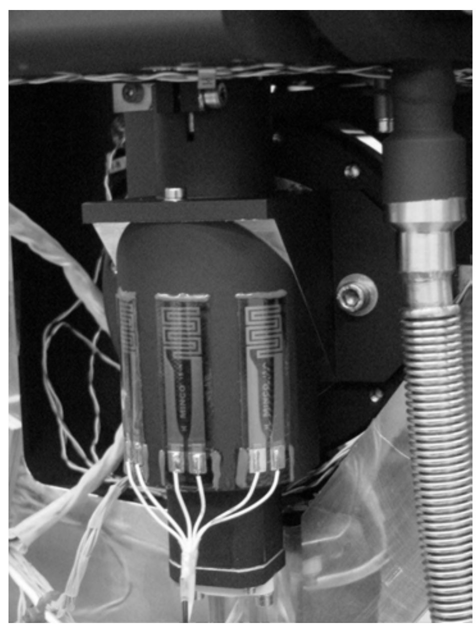

Figure 14: Active thermal control heater elements at the lamp of the visualisation system.

Active thermal control
The instrument requires an overall pointing accuracy of 50 micrometer, during approximately 45 minutes measurement duration. Therefore a variation in thermal equilibrium leading to deformation of sub-systems during measurement is critical for the Spot Scan. In order to maintain a thermal equilibrium the system is thermally actively controlled (Figure 14). The thermal control system has a combination of heaters and sensors in closed loop control, near the cooled baffle/shroud, diaphragm, support of the LN_2 vessel and at the table near the heated black body.

4. ACCEPTANCE TEST SET UP AND RESULTS

From a mechanical and thermal point of view, the following tests, part of the overall acceptance test program, are of interest:

- Positioning reproducibility of the cold diaphragm plate positions for VIS system, and CBFR / CT diaphragms during thermal cycling
- Spot position accuracy under thermal vacuum conditions

To enable performance of these tests, a dedicated test set-up has been designed, incorporating a calibrated plate and an IR detector set-up in the image plane of the OUVE (Figures 15 and 16). A switch between the 2 targets is simply achieved by a translation of the OUVE along the Z-axis.

The calibrated plate consists of a 80 x 80 mm gold coated plate, with accurately positioned (unique) markers, covering the complete Y, Z scan range (± 30 mm) of the Spot Scan OGSE. It is used in the following way: after initial visual alignment of the OUVE with respect to the central marker (0, 0), the OUVE is commanded to an extreme corner point, say (30, 30). The VIS system is then used to measure the offset between the (30, 30) marker and the commanded OUVE position.

The IR detector used is a 1 x 1 mm MCT (HgCdTe) detector operated at about -110 ºC for which the response curve more or less coincides with the IASI B3 band (3.62 – 5 μm). The detector is mounted in a collimator tube with an f/6.75 acceptance angle, representative with the IASI cold box.

VIS system and CBFR /CT diaphragm cold vacuum positions
A proper IR spot shape requires the CBFR and CT diaphragms to be in the focus of the relay mirror. Under ambient conditions, the corresponding positions of the diaphragm translation stage were simply determined by (temporarily) putting a laser at the position of the BB and projecting the resulting (laser) spot in the focal plane of the OUVE. The thus determined (ambient) positions however, will differ from the positions at operational thermal vacuum conditions because of the Aluminium diaphragm plate cool down from + 20 ºC to – 188 ºC and the resulting contraction. Also the VIS system position will shift from ambient to cold vacuum conditions, because the folding mirror of the VIS system is mounted on the cooled diaphragm plate

Prior to diaphragm cool down, the position of the VIS system reticle on the monitor was marked (Figure 17) and the reticle was aligned with respect to the center mark on the calibrated plate. After completion of the diaphragm cooldown, the reticle was re-aligned with respect to the center mark on the calibrated plate. The required adjustment in Z-direction (0.648 mm) is equal to the contraction of the diaphragm multiplied by the 1.75 magnification of the optical system. Thus, for the VIS system, the measured diaphragm contraction is 0.648/1.75 = 0.370 mm. The cold reticle position was updated in the Diaphragm-stage S/W look-up table accordingly. This approach was verified by selecting the newly determined VIS_cold diaphragm stage position and the original (prior to cool down) Z-stage position. Now the reticle again was aligned with the central marker of the calibrated plate.

The optimum cold-vacuum CBFR and CT diaphragm positions were determined with the help of the IR detector. First the mid position of the detector was determined with the VIS system and the corresponding Z-stage position was noted. Then the (ambient) position of the diaphragm was selected and the IR detector output was measured as a function of the Z-stage position. The Z-stage offset between the mid position of the response curve and the mid position of the detector (as measured with the VIS system) is used to correct the cold diaphragm position on the basis of its ambient position.

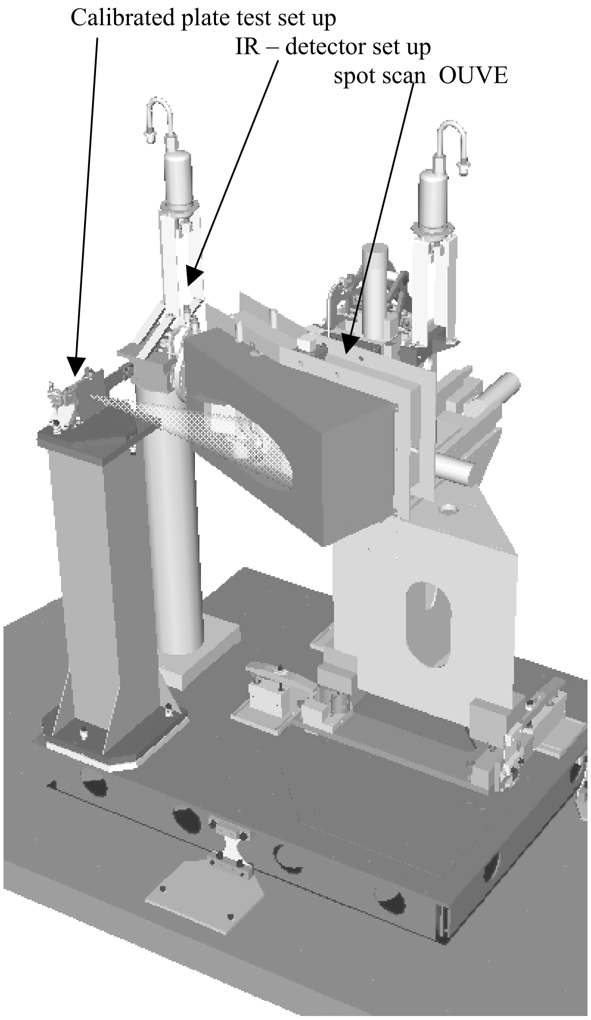

Figure 15: Spot scan OUVE and test devices integrated at test adapter.

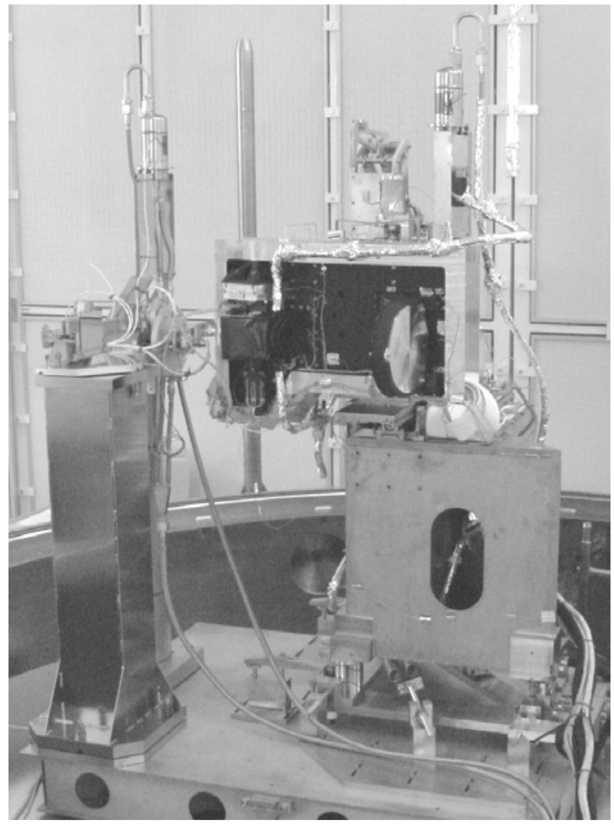

Figure 16: Spot scan OUVE during test.

Figure 17: Shift of VIS system recticle with respect to central marker (black) of calibrated plate due to diaphragm plate cool down from +20 ºC to -188 ºC.

Spot position accuracy

The calibrated reference plate is placed at the image plane of the OGSE. The OUVE was aligned with respect to the center mark and additionally with respect to 4 outer corner markers (Y, Z = ± 30 mm). For a number of measurement sequences, the middle corner markers (Y, Z = ± 15 mm) were used as well. After OUVE visual alignment with respect to each marker, the corresponding Y- and Z-stage positions were recorded. Measurements have been performed at different OUVE conditions: ambient, BB at 670 K and BB at 478 K.

Using the solver function of a spreadsheet, the raw measurements were corrected for:

- rotation (around X-axis) of the calibrated plate
- YZ shift of the calibrated plate
- non-orthogonality of Y and Z axes

The remaining RMS error for all markers in different OUVE conditions is summarized in Table 2.

BB temp	**# points at the reticle plate**	**rms error [mm]**
ambient	9	0.015
670 K	5	0.021
670 K	5	0.021
478 K	9	0.016
478 K	9	0.019

Table 2: Result summary of under vacuum spot position accuracy measurements.

To verify the pointing stability over time, for each BB temperature level, two series of measurements were performed. In between these two measurement series, a (virtual) pixel scan was performed of each pixel (2 mm/s scan speed). The central marker position was recorded in between each scan.

The position stability during 10 minutes period as well as the repeatability after moving to the parking position are within the resolution of the VIS system (about 5 µm).