Design, Development and Verification of the HIFI Alignment Camera System

E.C. Boslooper*, B.A. van der Zwan, B. Kruizinga, R. Lansbergen
TNO Science and Industry, P.O. Box 155, 2600 AD Delft, The Netherlands

ABSTRACT

This paper presents the TNO share of the development of the HIFI Alignment Camera System (HACS), covering the opto-mechanical and thermal design. The HACS is an Optical Ground Support Equipment (OGSE) that is specifically developed to verify proper alignment of different modules of the HIFI instrument during on-ground thermal (vacuum) testing of the ESA Herschell spacecraft.

Keywords: alignment measurement, optical design, mechanical design, thermal testing

1. INTRODUCTION

HIFI (Heterodyne Instrument for the Far Infrared) is one of the instruments to be flown on the ESA Herschell spacecraft due for launch in 2007. Heart of the spacecraft is a large cryostat vessel at 10 K in which the HIFI instrument Focal Plane Unit (FPU) is located. The heterodyne detection principle, involves transforming the frequency range of the astronomical signal being observed to a lower frequency where it is easier to perform the required measurements. Mixing the incoming signal with a very stable monochromatic signal, generated by the Local Oscillator Unit (LOU) and extracting the difference frequency for further processing do this. The Local Oscillator Unit is mounted on the exterior of the cryostat vacuum vessel (CVV) and has an operational temperature of 120 K.

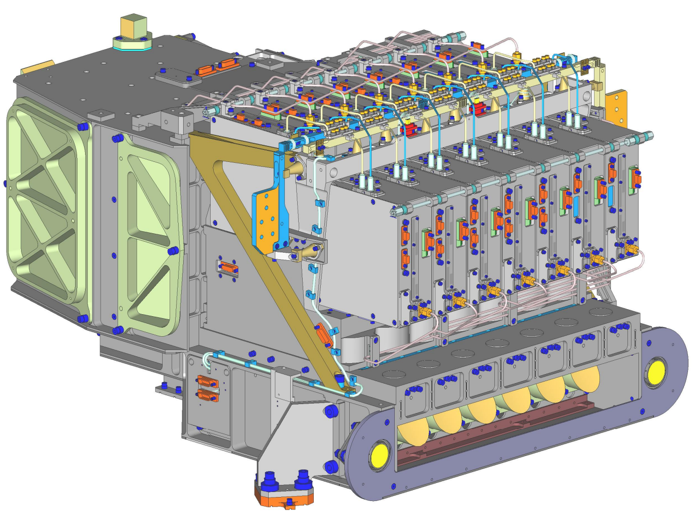

Figure 1. The HIFI instrument Focal Plane Unit

* erik.boslooper@tno.nl; phone 31 15 2692358; fax 31 15 2692111; www.tno.nl/space

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The Local Oscillator Unit (LOU) output is fed towards the Focal Plane Unit (FPU) inside the cryostat via 7 dedicated windows in the cryostat vessel, one for each of the frequency bands in which the instrument operates. Inside the FPU the LOU output is mixed with the science measurement signal from the telescope. The difference signal from the heterodyne process is passed to the instrument spectrometers. For optical alignment purposes, the CVV is equipped with two additional windows: one at each end.

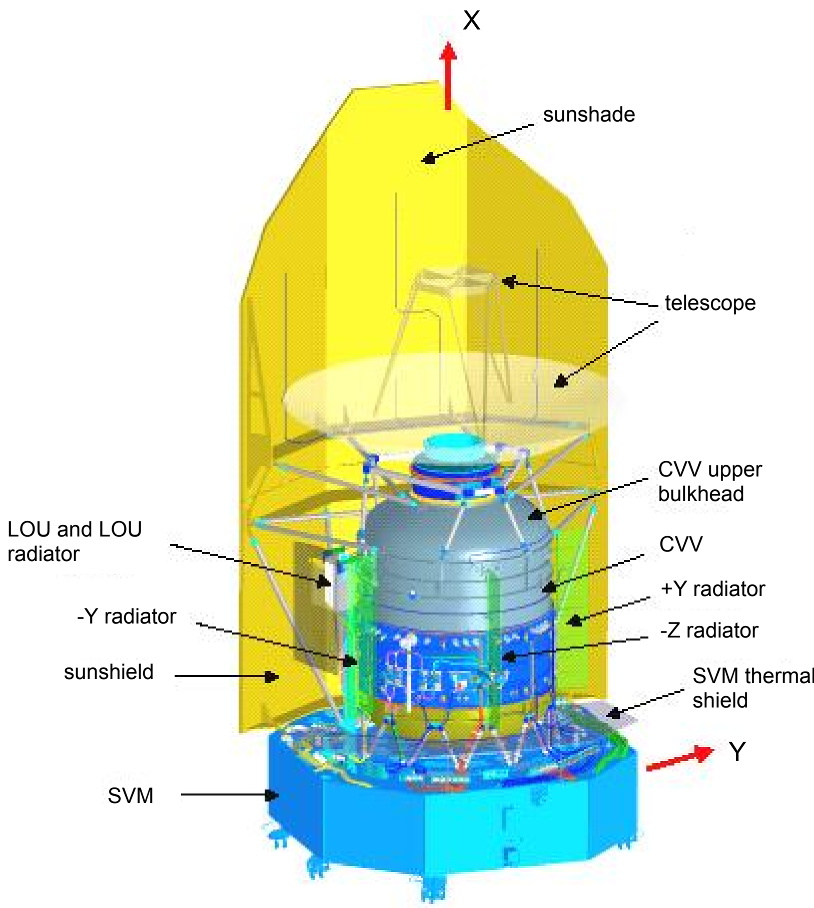

Figure 2. The Herschell spacecraft

The HIFI Alignment Camera System (HACS) is an OGSE that is specifically developed to verify proper alignment of the two units (FPU and LOU) of the HIFI instrument during on-ground thermal testing. The HIFI Alignment Camera System uses alignment devices (AD) mounted on both the FPU and the LOU to determine relative alignment between the two units. During spacecraft TB/TV testing, two cameras, suitable for operation at 120 K will be mounted on the LOU. The system is able to measure relative displacements between ambient and operational temperatures in six degrees of freedom with an accuracy of up to 0.1 mm for translations and 10 arcsec for rotations.

2. ALIGNMENT DEVICES

So-called alignment devices are mounted on both the instrument FPU and LOU. These alignment devices, which are integral parts of the HIFI instrument (not the alignment camera), are used for alignment during instrument AIT with a theodolite. During Herschell S/C TB/TV testing however, a theodolite cannot be used for alignment verification and a camera has to be used instead.

The FPU AD is a plano-convex lens, the curved side of which is mirror coated. Both the flat front surface and the concave mirror surface are used for reflection.

The LOU AD is a transmission optics part containing a dichroic coating separating red and green HeNe laser light as reflected from the FPU AD. The green light path contains a plano convex lens, whereas the red light path is does not contain any optical power. Further, the LOU AD is equipped with an optical flat, directly facing the camera. For alignment measurements with the theodolite, the optical flat is equipped with a crosshair.

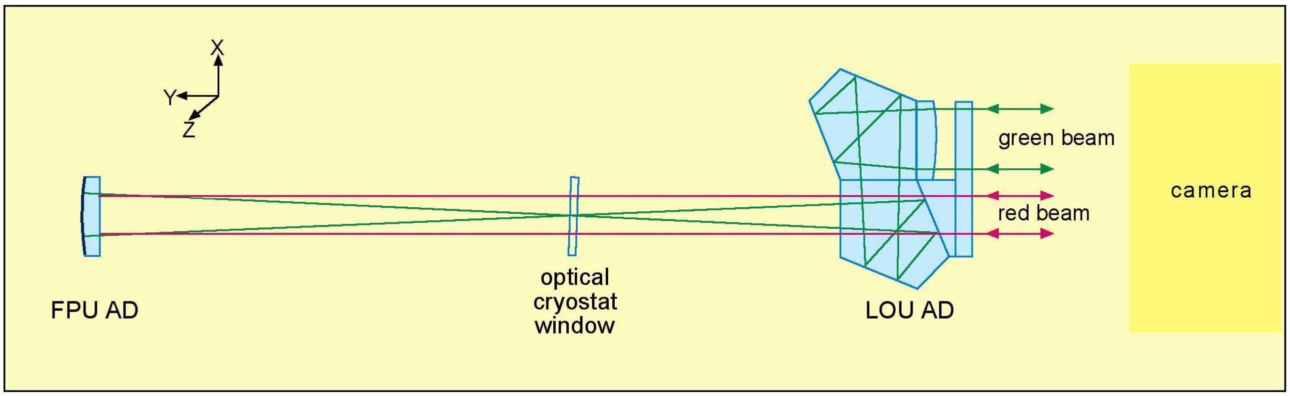

Figure 3. Alignment devices as mounted on the FPU (left) and LOU (right)

3. THE MEASUREMENT PRINCIPLE

These alignment devices can be used for rotation and translation measurements as follows.
For rotation measurements, a collimated red laser beam incident on the lower part of the (uncoated) optical flat of the LOU AD (see Figure 3) is partly reflected (~ 4%) and transmitted (~96%) without deviation towards the FPU AD. There it reflects both on the uncoated flat front surface (~ 4%) and on the concave mirror surface (~ 95%). The front surface reflected light is back reflected towards and transmitted through the LOU AD, whereas the light reflected on the concave mirror surface is diverted away. The net result is that two in general non-parallel beams are coming out of the LOU AD, the angle between them being dependent on the relative orientation of the LOU AD and FPU AD.

Translation measurements make use of a collimated green laser beam incident on the upper part (uncoated) optical flat of the LOU AD. The transmitted part of the light now passes a plano convex lens before it is transmitted towards the FPU AD. Now the front surface reflected light is diverted away, whereas the light reflected against the concave mirror surface is back reflected towards and transmitted through the green light path of the LOU AD. Likewise as for the red beam, the net result is that two in general non-parallel beams are coming out of the LOU AD, the angle between them being dependent on the relative displacement of the LOU AD and FPU AD.

In both the rotation as well as the translation measurements the two returned collimated beams are focused onto a detector by the HIFI alignment camera.

One of the strengths of the concept is that the actual measurements are based on the relative position of the two spots, that is, the reference spot (reflected against the optical flat of the LOU AD) and the measurement spot (reflected against the FPU AD). This measurement, based on the relative position of two spots, significantly decreases the requirements on the thermo optical stability of the camera system.

A translation along the optical axis can be determined by a change in the size of the measurement spot.

The 6th degree of freedom, a rotation around an axis parallel to the optical axis cannot be measured with a single camera. A 2nd identical camera is used to enable calculation of this rotation by combining the translation-X measurements of both cameras.

This overall concept was developed by TNO in response to the SRON (Space Research Organisation Netherlands: the instrument responsible party) need to align the two parts of the HIFI instrument. In this original concept, a focus alignment was not necessary for the HIFI instrument and therefore not foreseen. The Alignment Devices, being part of the instrument, are SRON responsibility. Responsibility for FPU – LOU alignment on spacecraft level resides at Astrium Germany. Astrium decided to place the contract for the HIFI Alignment Camera System at the Danish company TERMA with TNO as subcontractor for the opto-mechanical and thermal design. An additional use for the camera to Astrium is to support the Herschell telescope alignment verification. This requires, however, a focus measurement.

4. THE HIFI ALIGNMENT CAMERA SYSTEM

4.1 General

To make use of the above measurement principle, the HACS needs the following functionality:

- collimated red and green beams incident on lower respectively upper part of LOU AD
- imaging of reflected beams (two red beams during rotation and two green beams during translation measurements) on a detector
- image processing S/W

Apart from these functional requirements, for the Camera Head (i.e. the vacuum part of the system) to be mounted on the LOU support structure of the Herschell spacecraft, a number of interface requirements apply. The most constraining are: available volume, mounting interface, maximum thermal interface heatflow and thermal radiator orientation (+X direction). Furthermore, to minimize costs, for the CCD detector and the Printed Circuit Board (PCB) with the Front End Electronics, the existing TERMA startracker camera design had to be considered, which fixes the dimensions of the electronics module. Due to the fact that both AD's are H/W not part of the Alignment Camera, the beam diameter is about the only optical design parameter. And even that parameter has an upper limit dictated by external H/W.

4.2 Camera head

The HIFI Alignment Camera Head basically consists of three subassemblies:

- support bracket, which interfaces with the LOU support structure and contains one folding mirror
- optical module, which contains the remainder of the optical elements
- electronics module, which contains the CCD and PCB

In figure 4, the three subassemblies are clearly visible. On the optics module a tube is mounted, onto which an optical fibre is attached. The fibre tip is mounted in the focus of a doublet lens. The resulting collimated beam is incident on the so-called beamsplitter assembly, which is the main optical component in the optics module. The beamsplitter assembly transmits the incident collimated beam, such that the green light is incident on the upper part of the LOU AD whereas the red light is incident on the lower part of the LOU AD (figure 3). This separation is achieved via a dichroic coating, similar to the one in the LOU AD.
In the other direction, beams reflected against LOU AD optical flat or FPU AD respectively, are transmitted through the beamsplitter and imaged onto the CCD via a doublet lens and three folding mirrors. To suppress ghost images, a neutral density filter is included.

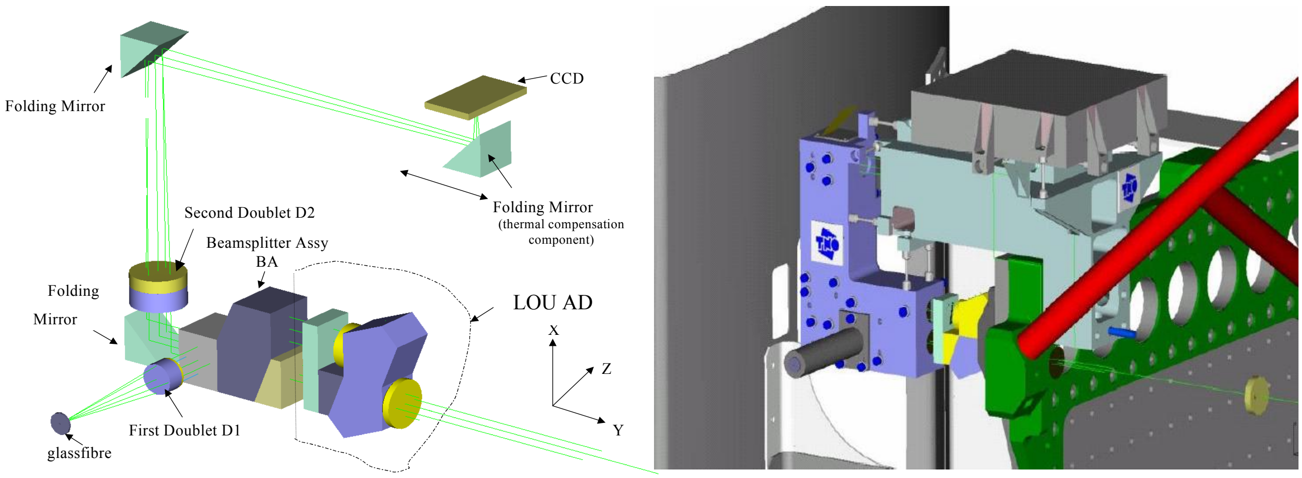

Figure 4. Optical components of the HIFI Alignment Camera Head (left) and CAD drawing (in the same orientation) of integrated unit as mounted on the spacecraft (right).

To ensure thermal compatibility over the complete temperature range experienced by the camera (120 – 300 K), the following measures are taken. The optics module and the optics mounts are made of Ti to match the glass Coefficient of Thermal Expansion (CTE) as good as possible. The support bracket on the other hand, is made from Al as it interfaces with the Al LOU support structure. The electronics module housing is made from Al as well. Further, passive thermal compensation mechanisms are included, to ensure the fibre tip and CCD to be in-focus, of the respective doublet lenses, at ambient and operational temperature conditions. The three subassemblies are interconnected by TiAlV struts (visible in figure 5) that provide:

- a minimal heatflow through the support bracket (and to the LOU support structure)
- a stiff and statically determined structure (high stability, very low stress)
- a coupling between the Al support bracket and the Ti optics module that provides a homogeneous temperature over the Ti optical module

The operating temperature of the PCB is in the order of –30 ºC, heat rejection is via a thermal radiator on the top of the electronics module housing.

The camera will also be used to check any orientation shifts that may have occurred during spacecraft vibration testing. To this end, reproducible mounting of the camera is ensured via dowel pins.

4.3 Light source Assembly

One optical fibre is connected to the optics module of the camera. The light source assembly consists of an external red and green HeNe laser, attenuators and fibre couplers, which enable the coupling of both lasers into a single fibre. The attenuators are controlled such that only one color is incident at a time (other laser output blocked by attenuator), allowing straightforward distinction between translation and rotation measurements.

4.4. Control computer and processing S/W

The PC interface electronics consists of a PCI based computer board which acquires images from the camera and performs all of the processing needed to generate images available to the PC software. Laser control is also performed via the PC. Measurement data processing essentially consists of two steps: raw spot detection and translation rotation calculation based on the relative positions of the spots. These calculations are based on look-up tables which were prepared with an optical model of the complete system.

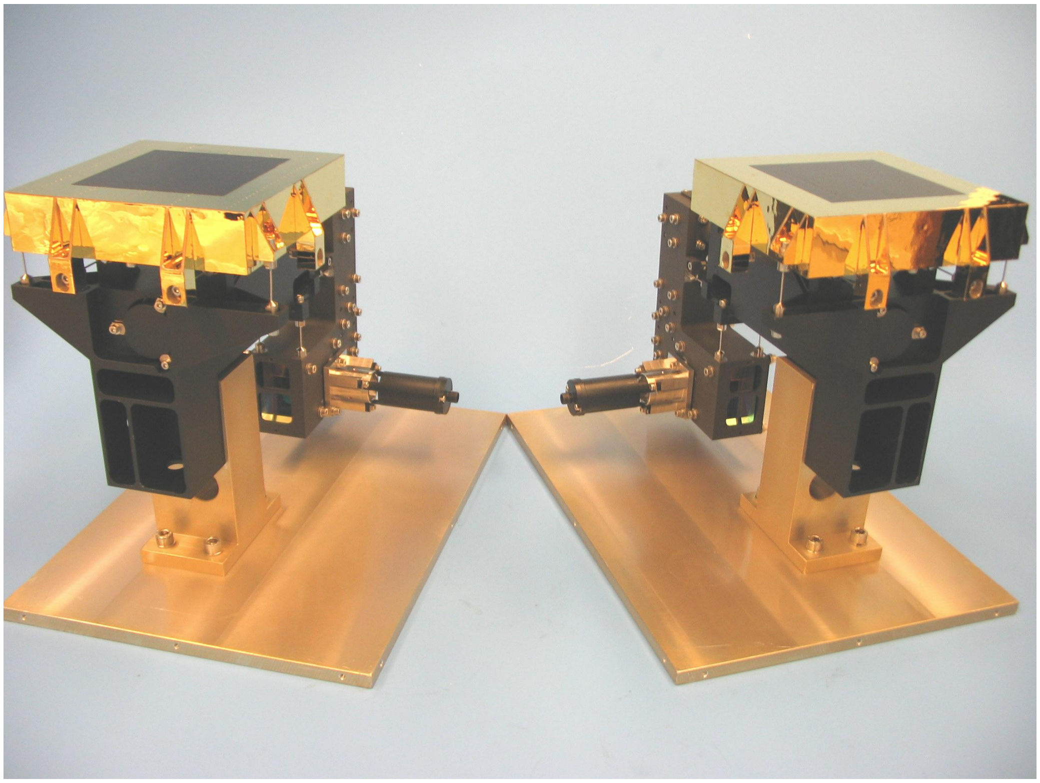

Figure 5. The completed HIFI Alignment Camera Heads (+Z on the left and –Z on the right) mounted on the transport/storage support.

5. TEST SET-UP

During the HACS system level test, the camera is mounted in a thermal vacuum (TVC) facility ensuring a representative thermal environment. The FPU AD is mounted on a set of translation-rotation stages in ambient, allowing straightforward displacement and/or orientation adjustment between the two alignment devices. Visibility between LOU AD and FPU AD is ensured via a small dedicated window in the TVC facility. Both camera (in vacuum) and FPU AD (in ambient) are mounted on a support frame, extending through a flange of the vacuum facility. This ensures optimum mechanical stability between the two. The test set-up is shown in figure 6.
In the test set-up, the conductive interface temperature of the camera's (120 K) is controlled via a dedicated LN2 circuit running through a copper plate onto which the dummy LOU support structure is mounted. The radiative interface temperature is controlled via the shroud of the TVC. Thermo mechanical deformation of the test set-up is minimized by keeping the vacuum part of the support frame ambient temperature throughout the test. For this reason it is equipped with wire heaters and wrapped by a Mylar foil for thermal insulation. Finally the test representation of the LOU support structure is mounted at the thermal center of the Cu plate which is thermally insulated from the support frame.

6. TEST RESULTS

Measurement range and accuracy were determined both under ambient and (cold) operational conditions. The accuracy achieved is well within specification.

The useful translation and rotation measurement ranges are determined by the size of the LOU AD and FPU AD optical apertures, whereas the optical quality of these devices determine the achievable accuracy, especially for the Y-translation measurement (focus direction). So, vignetting of the beam by the LOU AD, which occurs for larger deviations from the nominally aligned position, both limits the achievable accuracy and measurement range. Upon cooldown of the spacecraft during TB/TV testing, the LOU AD shifts relative to the FPU AD. Since proper alignment needs to be obtained at operational temperature, the relative position / orientation of the Alignment Devices at ambient conditions are put at an offset such that nominal alignment occurs at operational temperature.

A summary of the achieved ranges and accuracies is given in table 1. Note that the Y-rotation is actually calculated by combining the measured X-translations of the two cameras.

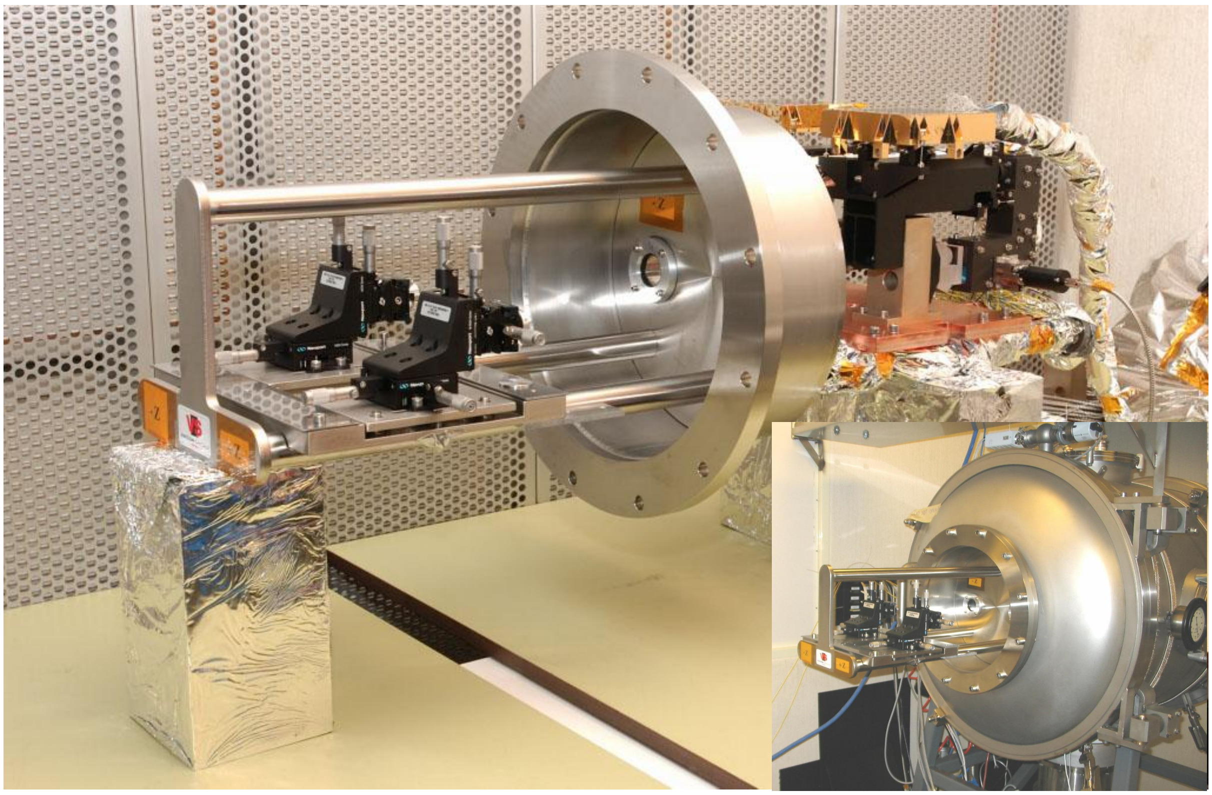

Figure 6. Vacuum test set-up

Table 1. Achieved measurement range and accuracy

parameter	achieved range	achieved accuracy
T_x	± 2,5 mm	0,1 mm
T_y	± 2,5 mm	0,65 mm
T_z	± 2,5 mm	0,1 mm
R_x	± 20 arcmin	< 10 arcsec
R_y	± 20 arcmin	< 40 arcsec
R_z	± 20 arcmin	< 10 arcsec

A translation along the optical axis can be determined by a change in the size of the measurement spot. Therefore the Y-translation measurement (focus direction) depends heavily on the optical quality of the Alignment Devices. It turned out that the optical quality of the Alignment Devices limit the system measurement accuracy in focus direction.

7. CONCLUSIONS

A system for relative alignment measurements in cryogenic vacuum environment in six degrees of freedom was developed and verified. The system is based on light beams that pass two optical devices, mounted on the respective between which alignment needs to be verified. Distinction between rotation and translation measurements is ensured by the use of beams of different wavelengths. The accuracy achieved is up to 0,1 mm for translation measurements and 10 arcsec for rotation measurements. The achievable range is determined by the optical aperture of the alignment devices.

ACKNOWLEDGEMENTS

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