Title: **Alignment Methods, Plan & Results**

CI-No: 120000

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1	13.04.04	All	First formal Issue (Based on Herschel Alignment Concept, HP-2-ASED-TN-0002) --	
2	21.12.04	All	Update according to H-EPLM CDR comments (RIDs). The following RIDs / AIs have been considered and recommendations implemented: RID 11006 (AI 11) RID 11157 (AI 09) RID 11094 (AI 12) RID 10997 (AI 13) RID 11003 (AI 15) Additionally the following has been corrected:	
		17	Coordinate system added	
		68	Coordinate system, y axis corrected	
		72	Sentence: Presently there is no approval……deleted. All changes are marked by a vertical bar. --	

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1 Introduction

Proper function of the three Herschel scientific instruments HIFI, PACS and SPIRE requires their precise alignment to the Herschel telescope focus. During the integration, however, the telescope is the last optical subsystem to be mounted upon and outside the cryostat if the cover has been already closed. Additionally the LOU has to be aligned w.r.t. the HIFI FPU.

As a consequence the instruments have to be aligned to an optical reference system without the telescope. When as the last step the telescope is integrated it will be aligned to the same reference.

Another constraint is that the alignment requirements are valid for in-orbit and cold conditions whereas the on-ground alignment can only be performed at warm conditions.

The most critical part of the alignment is the alignment of the LOU w.r.t. the HIFI FPU and the verification of the CVV shrinkage inside the TV chamber.

In this technical report we present the alignment concept for the Herschel payload which has been chosen in order to fulfil the alignment requirements, the alignment plan and the budget taking into account the above mentioned constraints.

The Herschel Satellite is shown in Figure 1-1.

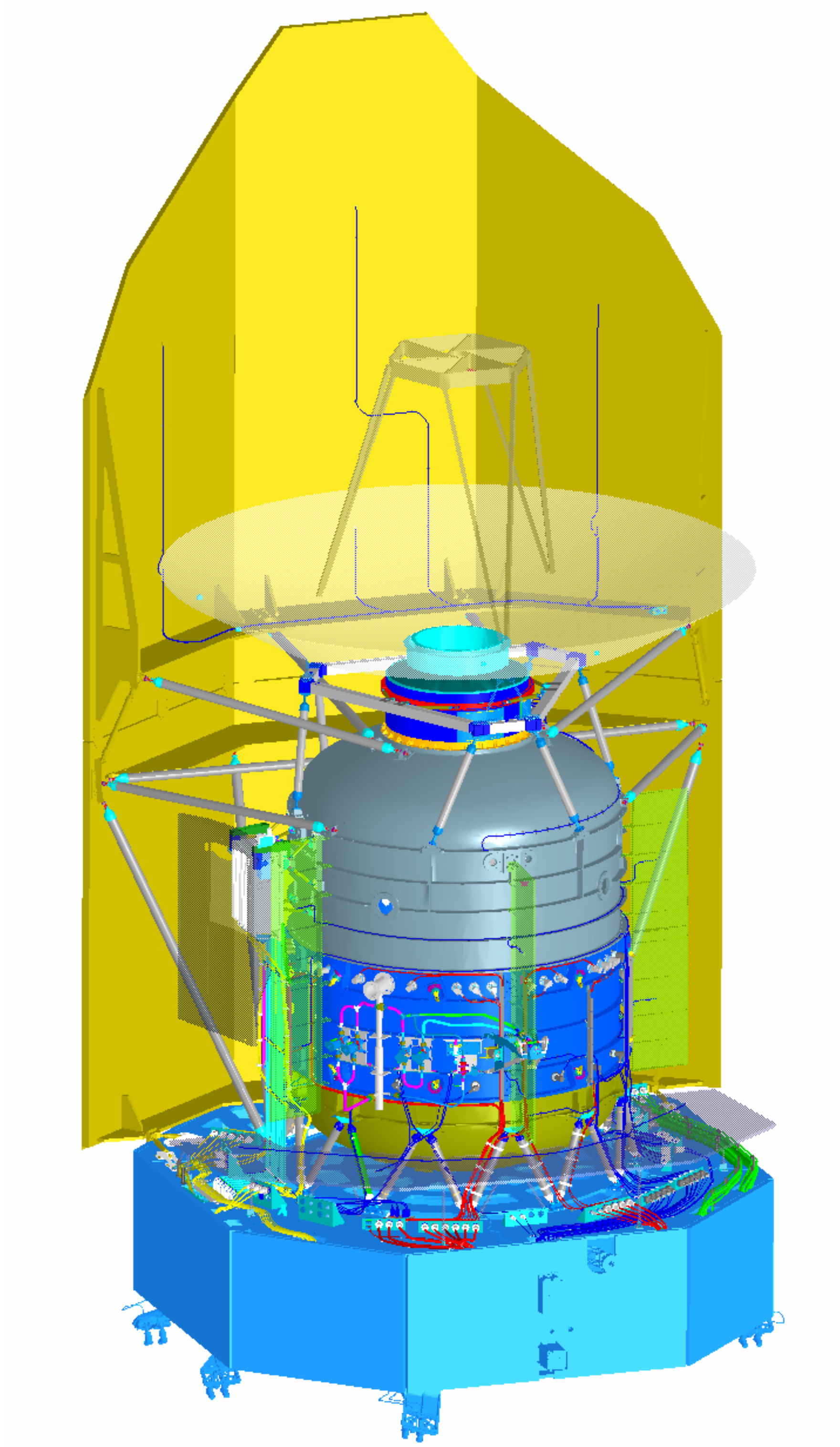


Figure 1-1: Herschel Satellite

2 Documents

2.1 Applicable Documents

[AD 1]	Instrument Interface Document IID Part A SCI-PT-IIDA-04624, Issue 3/0
[AD 2]	H-EPLM requirements Specification (HERS) H-P-2-ASPI-SP-0250
[AD 3]	Instrument Interface Document Part B, Instrument HIFI SCI-PT-IIDB/HIFI-02125, Issue 3.1
[AD 4]	Instrument Interface Document Part B, Instrument PACS SCI-PT-IIDB/HIFI-02126, Issue 3.1
[AD 5]	Instrument Interface Document Part B, Instrument SPIRE SCI-PT-IIDB/HIFI-02124, Issue 3.11
[AD 6]	FIRST Telescope Specification SCI-PT-RS-04671, Issue 6/0

2.2 Reference Documents

[RD 1]	HIFI – LOU Alignment Plan (Annex 2 in IID Part A, SCI-PT-IIDA-04624, Issue 1/0, dated 1.09.2000)
[RD 2]	HEPLM Thermal Distortion Analysis-FE Model Description and Results, HP-2-ASED-TN-0046
[RD 3]	Thermal Input to HEPLM Thermal Distortion Analysis HP-2-ASED-TN-0045
[RD 4]	H-EPLM Thermal Distortion Analysis - Trade of material and temperature variation H-P-2-ASED-TN-0061, dated 21.10.02
[RD 5]	Herschel PLM/EQM AIT Plan HP-2-ASED-PL-0022
[RD 6]	Satellite AIT Plan (Part 1: STM Qualification Phase) HP-2-ASED-PL-0025
[RD 7]	Herschel Satellite AIT Plan (Part 2: PFM Acceptance Phase) HP-2-ASED-PL-0026
[RD 8]	H-EPLM Thermal Model and Analysis HP-2-ASEd-RP-0011, issue 4, dated 15.04.04
[RD 9]	Alcatel Fax, H-P-2-ASP-LT-2728, dated 19.02.03
[RD 10]	HIFI e-mail, dated 24.05.02
[RD 11]	HIFI e-mail, dated 07.06.02

3 Alignment Requirements

The alignment requirements for Herschel are defined in the documents [AD 1] through [AD 6]. There are two constraints:

- The alignment requirements listed in the above mentioned documents must be fulfilled in space.
- The requirements are valid for operational conditions (OB at appr. 10K and LOU at appr. 135K), whereas the alignment will be carried out at ambient conditions. Only a check of the actual alignment is possible in operational conditions

An alignment concept and overall alignment strategy which takes into account the above mentioned constraints will be discussed in the next chapters.

The alignment requirements are subdivided into 4 major groups:

- General alignment requirements
- Alignment of Herschel Focal Plane Units w.r.t. Telescope
- LOU w.r.t. to HIFI FPU Alignment Requirements
- Requirements related to System Pointing Performance

3.1 General Alignment Requirements

R1 Alignment and Stability Requirements (HERS-0610)

The Herschel PLM alignment plan shall include as a minimum :

- Alignment requirements (coming from instrument needs and system needs
- For each requirement the contributors
- For each contributor the justification of the contributor
- For each requirement a dedicated budget
- A description of all the alignment sequences and relevant OGSE
- A list of the requirements specified to sub systems and OGSE

R2 The alignment of H-EPLM shall take into account the following causes of misalignments as a minimum (HERS-0620):

- Setting due to mounting procedure
- Setting due to launch distortions
- Gravity release
- Deformations caused by orbital temperature variation over the complete mission (including initial cool-down)
- Ageing
- Creep
- Composite structure deformation due to moisture release and radiation
- Pressure release

R3 **Alignment Cubes** (HERS 0680)

The H-EPLM shall be equipped with at least 2 optical cubes (1 nominal, 1 for redundancy). They shall represent the H-EPLM optical reference frame.

R4 **Visibility of Alignment cubes** (HERS-1240)

The optical references used for focal plane and telescope alignment shall be accessible during module and system AIT operations.

R5 **Error Summation Rule** (related to HERS-1220 and 1230)

The error summation rule shall be the following:

1) Bias	Quadratic
2) Instabilities	Quadratic
3) Uncertainties	Quadratic
4) Total sum (1+2+3)	Linear

The uncertainties shall be calculated for a confidence level of 95% unless otherwise stated.

3.2 Alignment of Herschel Focal Plane Units w.r.t. Telescope

R6 Budget (HERS-1210)
A global budget shall be built and maintained all along the project.

R7 Focus Alignment (HERS-1220)
The absolute in-orbit focus alignment distance between telescope focus and each scientific instrument shall be less than:

Instrument	Absolute alignment requirement
PACS	± 7.0mm
SPIRE	± 7.7mm
HIFI	± 8.5mm

R8 Pupil Mismatch (HERS-1230)
The absolute in-orbit pupil lateral mismatch in telescope M2 plane shall be lower than:

Instrument	Absolute alignment requirement
PACS	± 7.0mm
SPIRE	± 9.5mm
HIFI	± 24mm

3.3 LOU w.r.t. to HIFI FPU Alignment Requirements

The alignment and stability requirements for the LOU w.r.t. the HIFI FPU have been taken from the document [AD 2]

R9 Alignment Requirements for LOU w.r.t. HIFI FPU (HERS-1250)

Δx	Δy	Δz	Rx	Ry	Rz
±0.75mm	±15mm	±0.75mm	±0.038deg	1)	±0.038deg

1) The rotation error Ry will cause a lateral misalignment in x direction of z*sin(Ry). The Δx value includes already offsets due to any rotation Ry.

It is assumed that the HIFI and LOU internal alignment error does not contribute to this budget TBC by HIFI.

R10 Stability Requirements for LOU w.r.t. HIFI FPU (HERS-1250)

Δx	Δy	Δz	Rx	Ry	Rz
±0.075mm/ 100 s	±0.003mm/ 100 s	±0.075mm/ 100 s	±0.003deg/ 100 s	±0.04deg/ 100 s	±0.003deg/ 100 s

The very high stability along the y axis should be regarded as a goal, which may be verified by analysis.

3.4 Requirements related to System Pointing Performance

The following requirements are derived from System Pointing Performance needs and include the contribution of Telescope (I/F w.r.t. CVV) and CVV.

R11 PACS LOS Bias (HERS-0640)
The alignment bias of PACS Line of Sight with regard to the PLM-SVM interface frame shall be lower than ± 5arcmin (including ground and in-orbit effects)

R12 Around-LOS Bias (HERS-0645)
The maximum around-LOS alignment bias of each instrument with regard to PLM-SVM interface shall not exceed 12arcmin (including on-ground positioning accuracy, thermoelastic behaviour)

R13 SPIRE and HIFI LOS w.r.t. PACS LOS (HERS-0650)
SPIRE and HIFI in-orbit LOS shall be known with regard to PACS LOS with an accuracy better than ± 3.6 arcsec (TBC) (including on-ground alignment knowledge, in-orbit stability knowledge).

This requirement is related to the in-orbit knowledge accuracy of SPIRE (resp. HIFI) cubes w.r.t. the PACS FPU cube. It includes:

- On-ground relative position knowledge accuracy (y-z plane)
- In-orbit relative stability knowledge during cool-down (y-z plane)

- In-orbit thermoelastic behaviour (y-z plane)

- The relation between the yz instrument relative position knowledge and relative in-orbit LOS is the worst case focal length of the telescope.

This is the old formulation of this requirement. It must be formally updated by Alcatel and reflected in H-P-2-ASPI-SP-0250. A new calculation is shown on page 56.

R14 Around LOS Knowledge (HERS 0660)
The around LOS alignment of each instrument with regard to the PLM-SVM interface frame shall be known with an accuracy better than ± 0.5arcmin at 68% confidence level (including on-ground alignment knowledge, in-orbit stability knowledge).

R15 Instrument LOS w.r.t. CVV/STR Stability (HERS-0700 b)
During observation phase, the alignment stability of the instruments LOS w.r.t. the CVV/STR assembly interface plane shall be better than:

- 0.4 arcsec peak/peak around y (0.25 arcsec goal) over 1 month
- 0.2 arcsec peak/peak around z (0.1 arcsec goal) over 1 month
- ± 0.1 arcsec on 1 minute (± 0.02 arcsec goal) around each axis

taking into account worst case sun aspect angle variation. The CVV/STR assembly is assumed to be perfect.
The stability analysis shall be budgeted according to contributions as specified.

R16 Alignment Stability between CVV/STR I/F and SVM/PLM I/F between Lift-Off and Operational Mission (HERS-0702)
The alignment stability between the CVV/STR assembly interface plane and the SVM/PLM interface plane shall be better than 30 arcsec peak/peak around each axis. This includes all events between lift-off and operational mission (launch effects, cool-down effects,….).

R17 Alignment Stability between CVV/STR I/F and SVM/PLM I/F during Observation Phase (HERS-0704)
During observation phase, the alignment stability between the CVV/STR assembly interface plane and the SVM/PLM interface plane shall be better than 6 arcsec peak/peak around each axis over one month taking into account worst case sun aspect angle variation and temperature gradient at SVM/PLM interface.

3.5 Responsibility Share

The responsibility share between Telescope, Instrument and CVV alignment contribution is shown for axial focus alignment and pupil mismatch as agreed during the HOWG meeting, dated 11.03.2002.

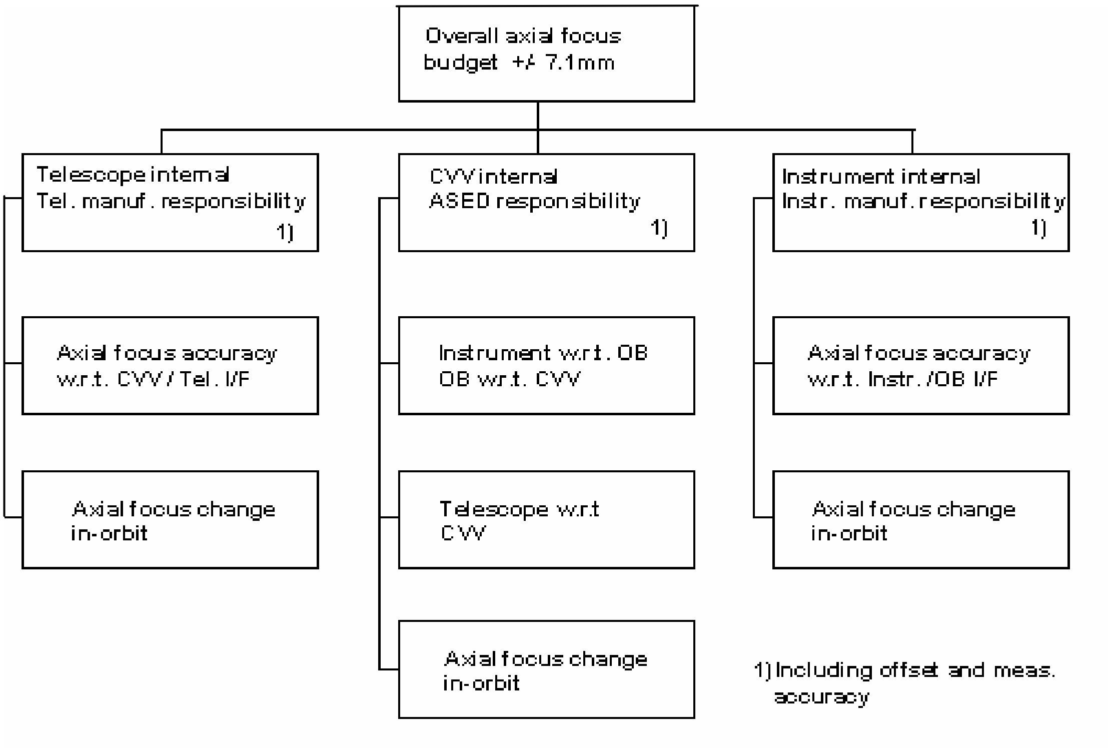


Figure 3.5-1: Responsibility Share for Axial Alignment

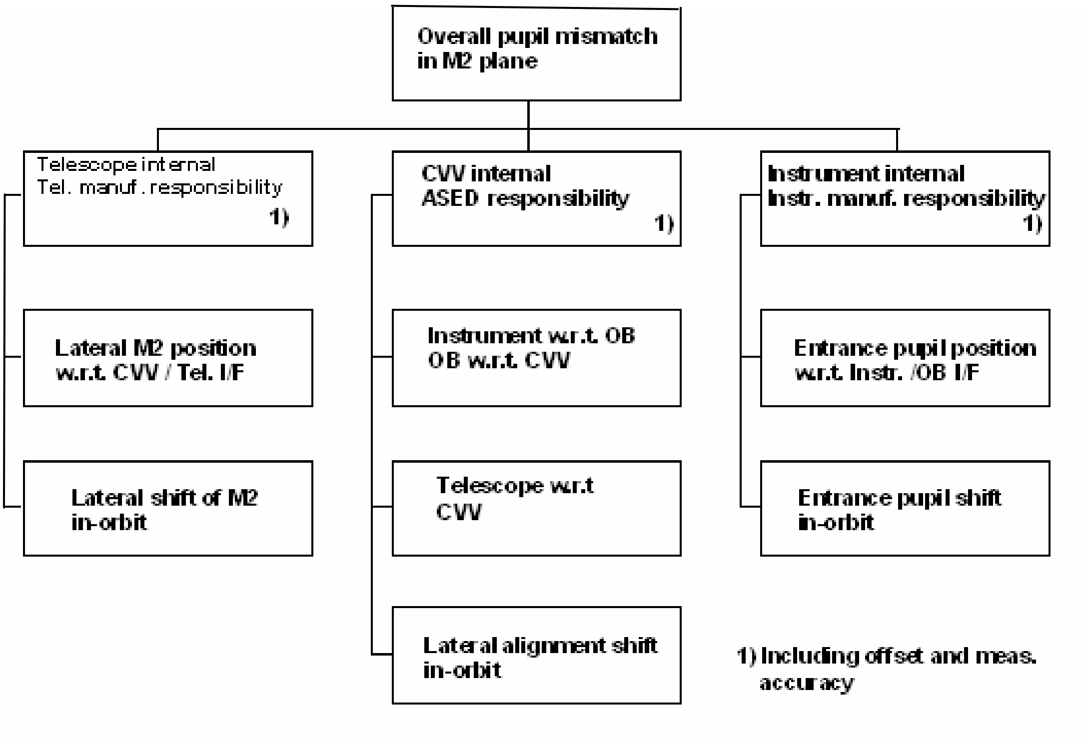


Figure 3.5-2: Responsibility Share for Pupil Mismatch

4 Herschel Alignment Concept

In this chapter we provide a description of the Herschel alignment concept. The alignment concept described below is chosen such, that except the HIFI Alignment Camera, conventional alignment tools can be used.

The measurement of the internal instrument and telescope alignment are under the responsibility of the manufacturers and are not covered within this document. However, the internal budgets have been considered in the overall system level budget in chapter 6.

4.1 Alignment Overview

The three Herschel instruments HIFI, PACS and SPIRE must be placed precisely at the telescope focus and the LOU must be aligned very precisely to the HIFI FPU. Therefore an instrument alignment must be performed w.r.t. the telescope focus during the system level integration activities.
During the Herschel integration, however, the telescope is the last subsystem which will be mounted outside and upon the cryostat. At this integration stage the cryostat cover is already closed and therefore the optical reference from the instruments can no longer be seen. Consequently the instruments must be aligned to a common intermediate optical reference to which the telescope is aligned later on. The main integration and alignment steps are as follows:

1. Mounting of a reference cube at the optical bench.

2. Integration of the OB into the cryostat.

3. Adjustment of the OB w.r.t. the LOU windows 1)

4. Integration of the three instruments onto the optical bench. Each instrument is equipped with an alignment cube to represent its internal alignment (see Figure 4-1).

5. Alignment measurement of the instruments w.r.t. the OB reference cube as shown in Figure 4-2 to know the actual orientation (position and angle) or directly to the CVV cube (step 6). 2)

6. Alignment measurement of OB reference cube w.r.t. a reference cube mounted outside the CVV (see Figure 4-3). If necessary correction of OB via the tank straps.

7. Closing the CVV and cryo cover

8. Alignment check via LOU windows

9. LOU integration and alignment measurement w.r.t. the HIFI FPU via two additional alignment windows using theodolite (as shown in Figure 4-4 and 4-6). If necessary adjustment of LOU w.r.t. HIFI using the LOU mounting struts.

10. Evacuation and cool-down.

11. Re-adjustment of the tank straps under alignment control via LOU windows Apply correct pretension for tank straps for in orbit conditions.

12. Telescope integration.

13. Alignment measurement of the telescope reference cube w.r.t. the CVV cube as shown in Figure 4-6. If necessary adjustment.

14. Environmental testing (TB/TV, Vibration, Acoustic Noise).

15. Alignment check before and after environmental testing.

1) The LOU must be aligned w.r.t. the HIFI FPU via the seven LOU windows. It is not possible to align the windows w.r.t. CVV. Therefore, the OB (HIFI) must be aligned w.r.t. the LOU windows.

2) According to IID-A the instruments shall be delivered with dowel pins. This is actually the case for PACS and HIFI. For SPIRE special screws will be used. That means, that the actual lateral position will be measured w.r.t. the OB and CVV but shimming is only possible in x direction. The instrument internal alignment error must be compliant with this alignment strategy.

The complete integration, alignment and test logic flow is shown in the Satellite AIT Plan, [RD 5-7].

To compensate for the variation in focal length and manufacturing tolerances the telescope and the instruments shall be delivered with shimming plates. The instrument shimming plates can also be used for angular corrections if necessary.

Dowel pins mounted at the OB and the telescope I/F to the CVV shall serve as alignment reference to allow to find the alignment position again after removing of the instruments or the telescope (e.g. for reproducible re-integration).

The measurement principle is explained in the following figures.

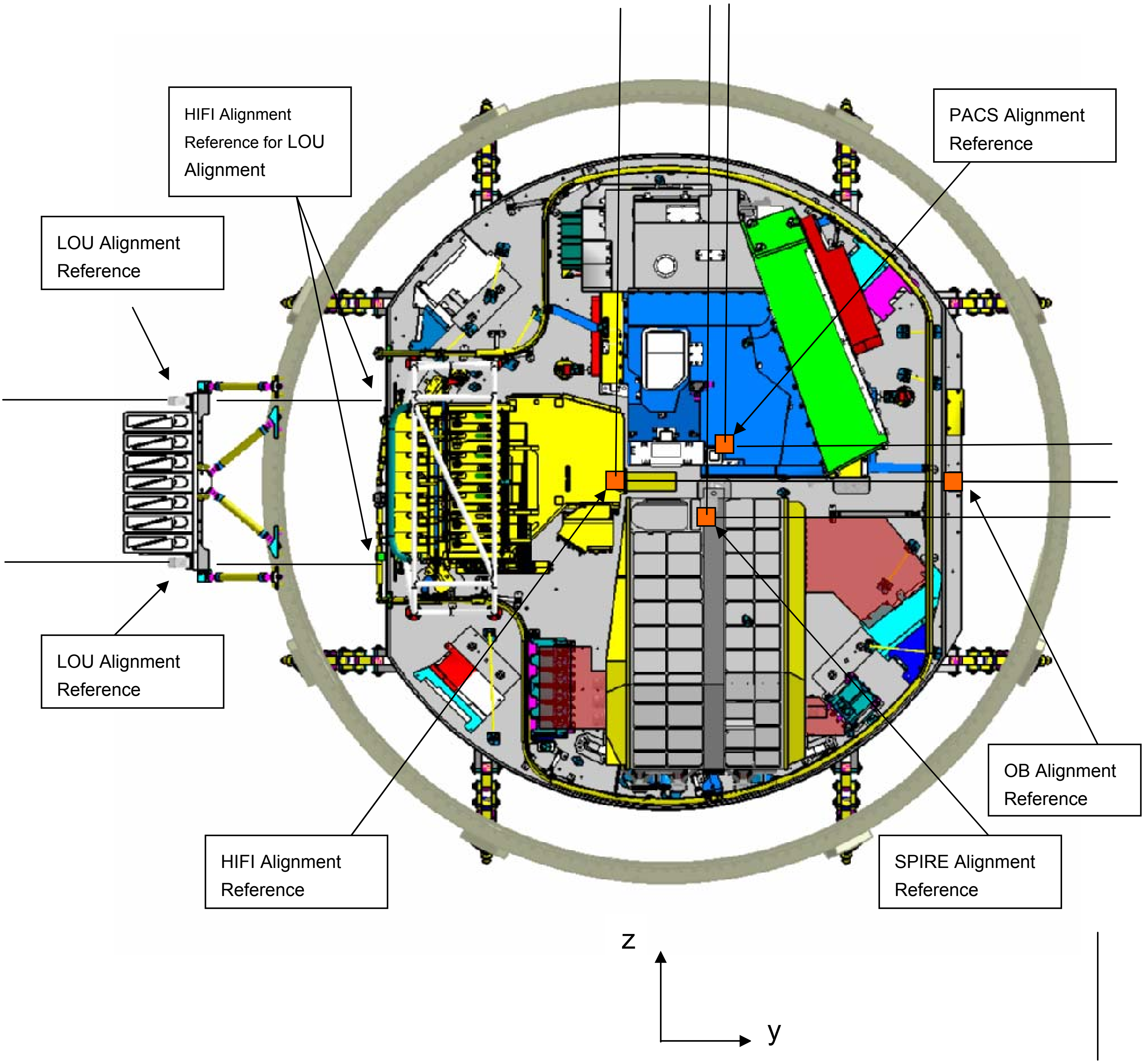
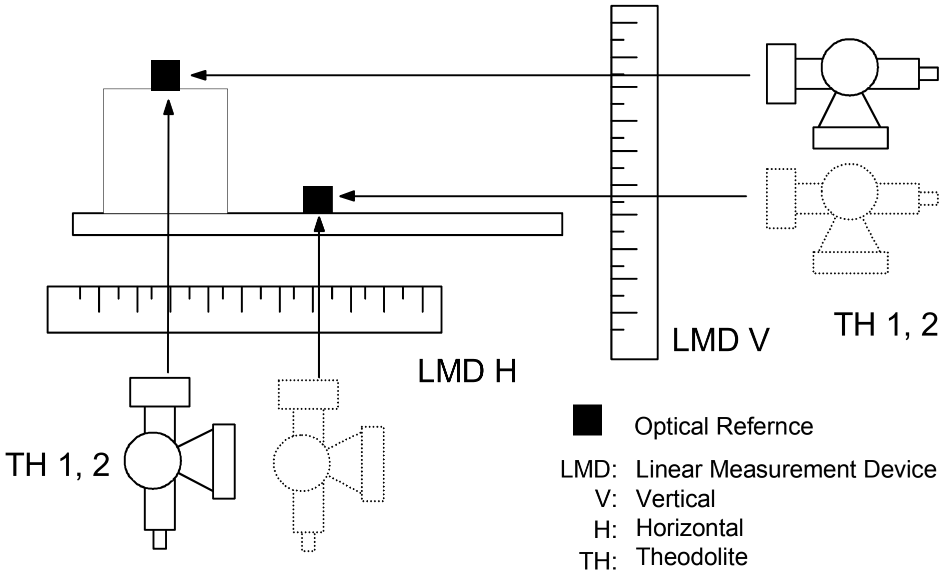


Figure 4-1: Alignment References for Instruments, LOU and Optical Bench



■ Optical Refernce

LMD: Linear Measurement Device
V: Vertical
H: Horizontal
TH: Theodolite
1, 2: Position 1, 2

Figure 4-2: Instrument Alignment w.r.t. Optical Bench

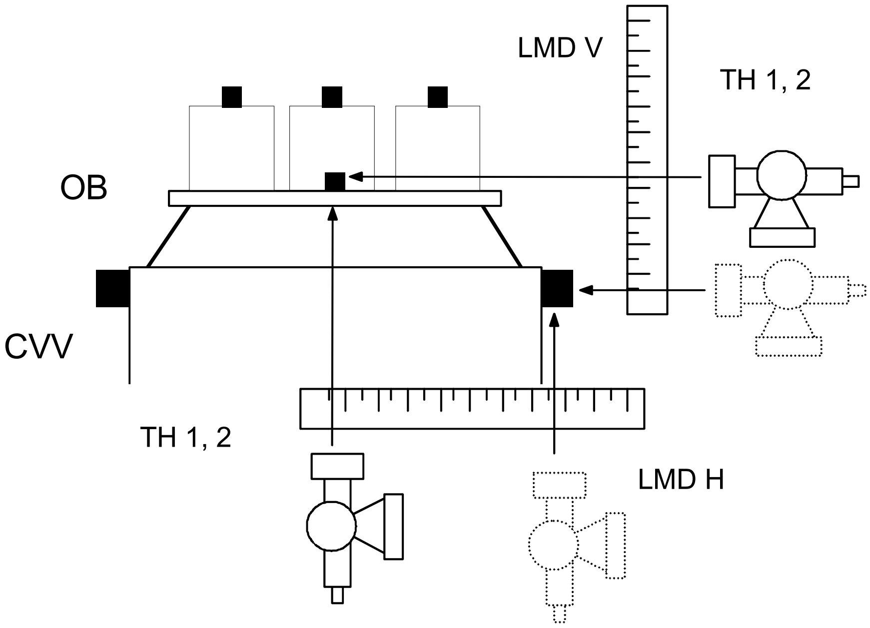


Figure 4-3: Optical Bench Alignment w.r.t. CVV

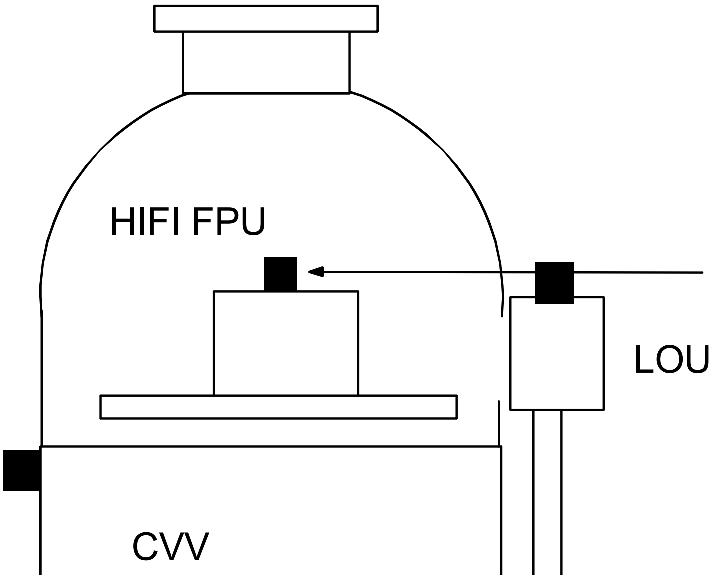


Figure 4-4: LOU Alignment w.r.t. HIFI FPU
(With the LOU Camera proposed by, HIFI TBC by HIFI)

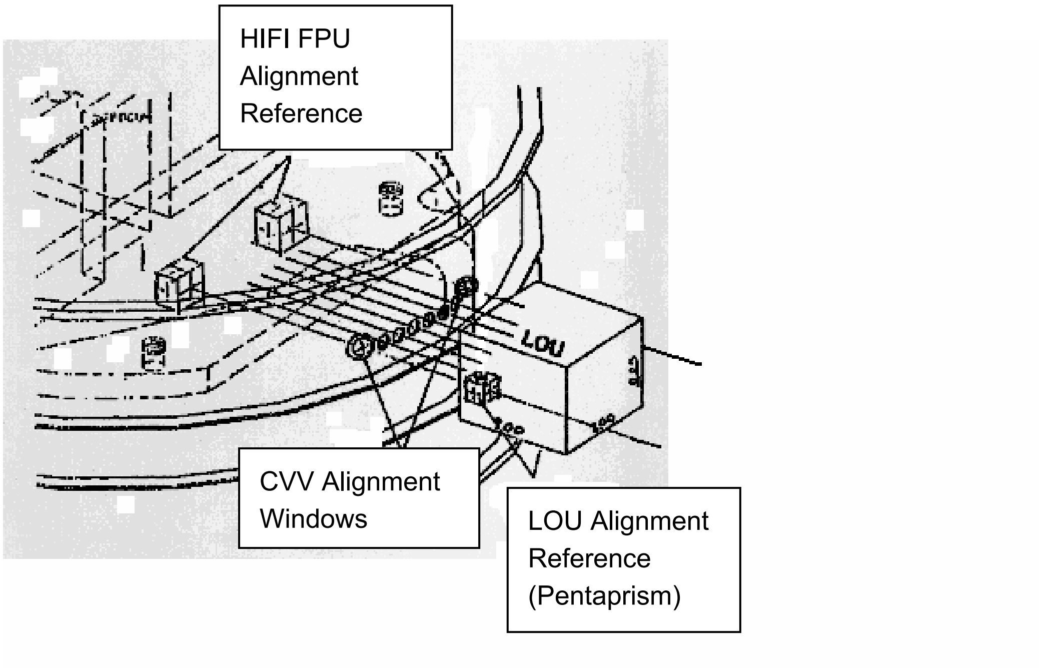


Figure 4-5: LOU Alignment w.r.t. HIFI FPU

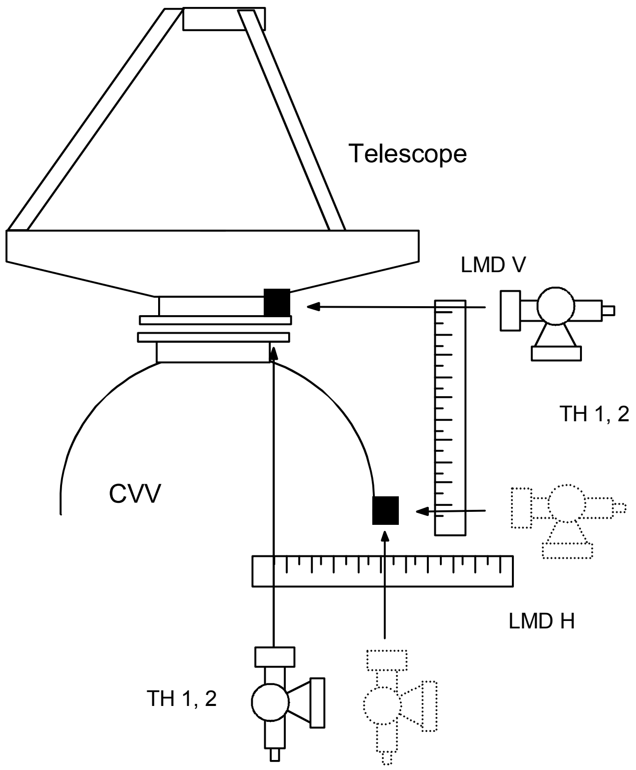


Figure 4-6: Telescope Alignment w.r.t. CVV Reference Cube

The alignment cube position of the instruments, OB, CVV and telescope will be defined in chapter 7.

4.2 Adjustment capabilities

For actual correction of the alignment measurements the following adjustment capabilities are foreseen.

1. Shimming plates for each instrument
    - PACS shim thickness ±3mm in x direction
    - HIFI adjustment range ± 3mm
    - SPIRE: No Shimming plates are foreseen

2. Optical Bench adjustment range in each direction 1.5mm via the 16 tank straps. Additional ±2mm in x direction using shimming plates between OB and upper Spatial Frame Work.

3. Telescope
    - Shimming plates at telescope side of mounting structure with ±5mm range
    - Shimming plates at the CVV side of the mounting structure
      Adjustment capability of +1.6/-1.8mm in x direction.
      Lateral adjustment capability of 2mm radius.

4. LOU adjustment capability w.r.t. CVV via the mounting struts of ±3mm in x and z direction and ±2.5mm in y direction.

The adjustment capabilities for the optical bench, telescope and LOU will be used in order to achieve the alignment requirements. The instrument shimming plates will only be used in case of internal instrument alignment correction or in case that the optimal position w.r.t. the focus for all three instruments cannot be achieved with the adjustment of the OB.

The following tables list the main tolerances to be taken into account for the definition of the adjustment ranges (struts and shimming plates):

1. Instrument w.r.t. Telescope:

H/W	Tolerance x [mm]	Tolerance y,z [mm]	Remark
CVV flange I/F to TMS strut I/F	± 0.6	± 0.6	
TMS strut I/F incl. TMS frame	± 0.5	± 0.5	
Strap I/F to CVV flange	± 0.3	± 0.3	
Suspended mass	± 0.5	± 0.5	
Worst case tolerance (lin sum)	± 1.9	± 1.9	
Shrinking between on-ground alignment and in-orbit	1.77	1)	To be pre-compensated during on-ground alignment
Adjustment range	± 5.1	± 3.5	Struts, shims; without Instrument shims

1) Compensated by instrument cold →warm I/F dimensions w.r.t. OB.

For the Telescope internal alignment separate shimming plates are foreseen by the Telescope manufacturer.

The Suspended Mass will be pre-aligned during Cryostat integration. Therefore the tolerances of the suspended mass components will not contribute.

2. LOU w.r.t. HIFI FPU:

H/W	Tolerance x [mm]	Tolerance y [mm]	Tolerance z [mm]	Rx [arcsec]	Ry [arcsec]	Rz [arcsec]
CVV flange to LOU Window	± 0.2	± 0.2	± 0.2			
CVV flange to LOU strut I/F	± 0.2	± 0.2	± 0.2			
LOU strut to LOU baseplate	± 0.1	± 0.1	± 0.1			
Worst case tolerance (lin sum)	± 0.5	± 0.5	± 0.5			
Shrinking between on-ground alignment and in-orbit	1.17	2.2	0.62	10.0	0.89	59.1
Adjustment range via support plate struts	± 3	±2.5	± 3			

4.3 Alignment Method

The alignment measurements can be subdivided into two major categories:

- Linear measurements (axial and lateral)
- Angular measurements (tilt and roll).

The angular alignment is subdivided into tilt measurements (rotation about the y and z axes) and roll measurements (rotation about the x axis). For both measurements standard optical cube and autocollimation techniques will be used except for the LOU alignment. To allow this two sides of an optical reference cube must be accessible as a minimum. One side for the rotation about the y axis and the other for the rotation about the z axis. The roll measurement can be performed from both sides.
The internal instrument alignment shall be performed from the same directions in order to minimise the error.

4.3.1 Angular Measurements

Because autocollimation measurements are standard this chapter gives only a short description. A theodolite is set in autocollimation at the first reference cube (for example OB). A second theodolite (or the same) is set in autocollimation w.r.t. the second reference cube (for example instrument). The difference from both readings gives the angle between both reference cubes taking into account the theodolite internal horizontal calibration (for rotation about the y and z axes). For roll measurements an additional outer reference such as an angular transfer prism must be used as reference for both measurements (to transfer the angular measurements from one cube to the other).

The use of an angular transfer prism is explained as an example for the roll measurement of an instrument w.r.t. the OB reference cube (see Figure 4-8). A theodolite is set in autocollimation w.r.t. the OB reference cube. The theodolite is then rotated by 90° in order to adjust the angular transfer prism (rotation of the ATP about the x axis until autocollimation is achieved). This defined direction can be picked up by a second theodolite performing autocollimation w.r.t. the ATP. Rotating this theodolite by 90° and looking in autocollimation onto the instrument reference cube determines the angular difference between the OB reference cube and the instrument.

4.3.2 Linear Measurements

For the linear measurements in focus direction and laterally all reference cubes shall have cross hairs. For the position measurements a linear measurement device will be used. The same device will be used for measurements in x- and y-z direction. It works as follows:

A scale tape (steel) is mounted onto a rail under a defined mechanical tension (spring load). On the tape surface are engraved code bars which provide an absolute linear position code. The actual position is defined by aiming sequentially at position reference cubes with cross hair on the PLM and an alignment target at the linear measurement device with a theodolite. The actual position is read by a scanning head and shown on a display. Figure 4-7 shows a typical linear measurement device and Figure 4-8 its application for a lateral measurement.

This linear measurement device is already available at Astrium. The length is appr. 2m. It has been designed and successfully used for XMM and is now in use for METOP. The measurement accuracy achieved was ± 0.2mm, but depends on calibration. Errors introduced by non perfect alignment of the linear measurement device w.r.t the relevant alignment axis defined by the PLM must be considered additionally.

Some modifications concerning the LMD support structure are necessary to use the LMD for axial and lateral measurements.

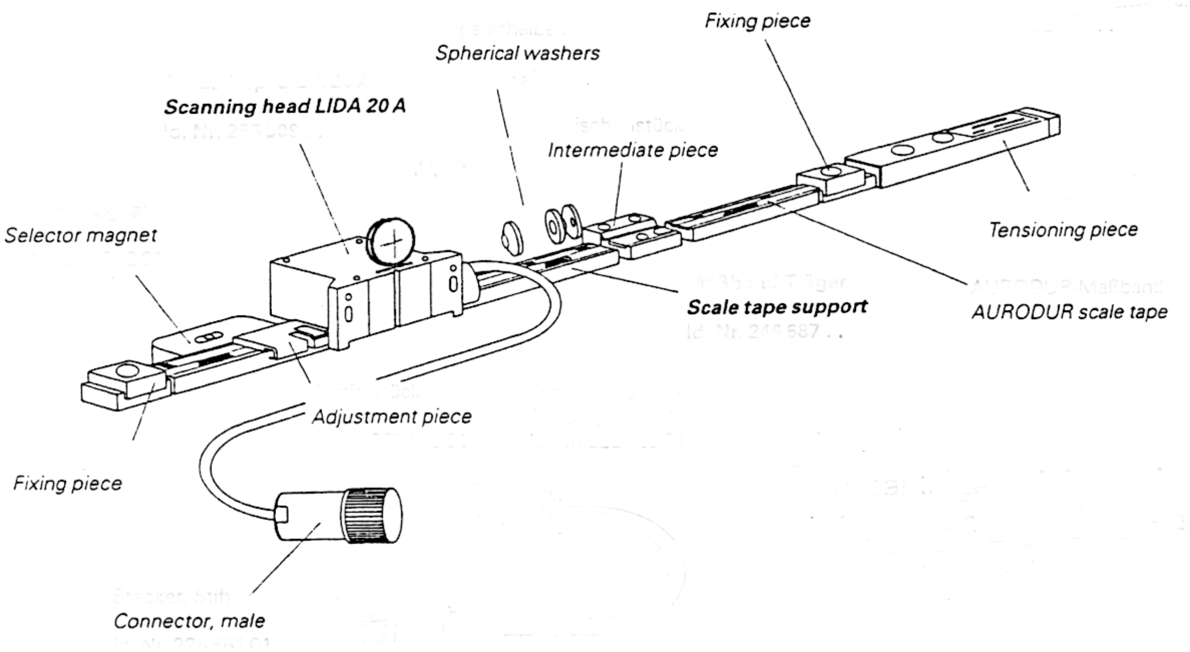


Figure 4-7: Linear Measurement Device

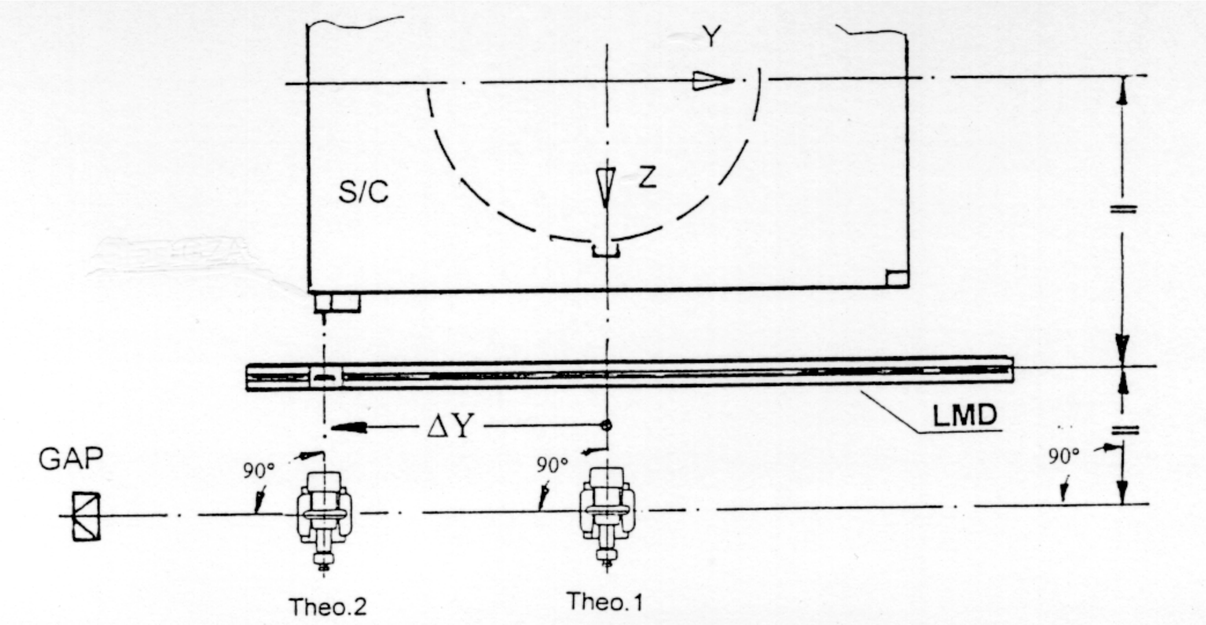


Figure 4-8: Lateral Distance Measurement using a LMD

4.3.3 Dedicated Alignment Tools

Beside the conventional Alignment Tools described above the following devices will be used to ensure that the alignment requirements are achieved at nearly operational conditions.

4.3.3.1 Measurements with HIFI Alignment Camera

The most critical alignment of LOU w.r.t. the HIFI FPU will be monitored inside the TV chamber at nearly operational conditions. For this purpose two alignment cameras are mounted temporarily on the LOU allowing to monitor simultaneously tilt and offsets between HIFI FPU and LOU alignment references. Two cameras are needed to determine the rotation about the y axis.

The HIFI Alignment Camera will be used at the following stages during the whole AIV programme:

1. Alignment check of LOU w.r.t. HIFI FPU inside TB/TV chamber at nearly in-orbit conditions. Based on this measurement, verification of CVV shrinkage and confirmation of FEM.
2. Indirect alignment verification of PACS and SPIRE via HIFI measurement.

This measurement will be performed with the STM and the PFM.

4.3.3.2 Measurements using Videogrammetry for PFM

On ESA request a measurement between Telescope and LOU has been implemented in order to verify the Telescope cool-down behaviour w.r.t. the LOU inside the TV chamber. No direct method of measuring the Telescope w.r.t. the Instruments (inside the CVV) is possible. Therefore a measurement of Telescope w.r.t. LOU is planned. For this measurement videogrammetry will be used.

A set of (two) cameras is located inside the TV chamber. Targets are placed on the Telescope (rim of M1) and the LOU. The satellite will be rotated about the z axis and the targets will be seen under different angles. The target position can be located via triangulation. Two measurements will be performed, one at ambient and the second after cool-down. The difference of both measurements is the movement of the Telescope w.r.t. the LOU due to cool-down.

Please note, that this test is not an end to end test, because the telescope is aligned to the instruments. But it can be compared to FEM results and increase the confidence of this model.

Measurements using Videogrammetry can only be performed with the PFM because the Telescope TM is not suitable (stability) for this measurement.

4.4 Alignment Strategy

In the frame of the system level alignment activities mainly 4 different alignment tasks have to be performed:

1. Focus Alignment
2. Pupil Mismatch
3. Line of Sight requirements
4. Alignment of LOU w.r.t. the HIFI FPU

The alignment responsibility can be shared into 3 parts:

1. Internal Instrument Alignment (Instrument supplier responsibility)
2. Internal Telescope Alignment (Telescope supplier responsibility)
3. Integration and alignment of Instrument and Telescope to PLM. (Astrium responsibility)

The Instruments and Telescope internal alignment will be verified by the Instruments and Telescope manufacturer. Reference will be made to an alignment cube mounted at the outside of the Instruments and the Telescope which are visible during all system level alignment activities.

In order to fulfil the 4 alignment requirements above careful budgeting and provision of (independent) adjustment capabilities have been foreseen. Therefore the following adjustment capabilities have been foreseen for system level alignment:

1. Shimming plates for PACS and HIFI
2. Adjustment of OB via the 16 tank struts
3. Adjustment of Telescope via shimming plates and bushings
4. Adjustment of LOU support structure w.r.t. CVV using the struts.

Because it is not possible to align the LOU windows w.r.t. the CVV, the OB must be aligned to the LOU windows as the first alignment step. For this purpose margin has been added on top of the LOU free beam diameter of 30mm. The max. possible window diameter is 34mm, which is limited by the pitch of the seven LOU channels. Once the OB is aligned in this position, only small changes are allowed w.r.t. this position. At this stage it is not allowed to apply the complete pretension to the tank struts because the CVV is not closed.

At the next step the Instruments will be integrated to the OB and measured w.r.t. an alignment cube mounted outside the CVV (position and angular deviation). No lateral correction of individual Instruments is possible because the Instruments are mounted via dowel pins onto the OB (except SPIRE). Only adjustment in x direction is possible

using the Instrument shimming plates. Corrections for the complete OB can be achieved using the tank struts (having in mind the window constraints).

After this alignment step the CVV will be closed. Now it is possible to perform the LOU w.r.t. the HIFI FPU alignment via the two additional alignment windows in position 0 and 8 beside the 7 LOU windows. Adjustment in each direction is possible as well as angular correction) using the LOU support structure mounting struts.

The CVV will now be evacuated and cooled down. During cool down the pretension of the tank struts will change and a re-adjustment is necessary. Now the correct pretension will be applied for in-orbit conditions. This will change the position of the OB and therefore this activity has to be performed with alignment control (two constraints have to be fulfilled at this stage: alignment of OB and correct pre-tension of the 16 tank struts).

Once the OB with the Instruments is adjusted the only possibility to bring the Instruments in the Telescope focus position is to align the Telescope. This will be achieved by measuring the telescope to the same alignment reference cube as the Instruments before closing the CVV cover. After the Telescope verification measurements the Telescope internal misalignment is known. This and the already achieved Instrument alignment status will be used and taken into account if the Telescope mounting structure is integrated. When the Telescope is integrated as the last step, the alignment should be within the requirements, which will be verified using the Telescope alignment reference cubes.

To guarantee the telescope I/F flatness requirement, a special TMS mounting tool will be used for TMS integration.

From the measured deviations between Instrument and Telescope position and angular deviation the misalignment in x direction, pupil mismatch and PACS LOS deviation can be calculated and compared with the requirements. In case corrections are necessary there must be an optimisation between pupil mismatch, LOS and LOU w.r.t. HIFI FPU alignment. Priority has the OB w.r.t. the CVV Windows. Within the tolerance frame of this alignment activity pupil mismatch and LOS can be improved. The LOU has a separate adjustment capability (see above) and can be treated therefore more or less independent from focus, pupil mismatch and LOS alignment, so that the optimisation is only related to pupil mismatch and LOS. The LOS requirement (HERS-0640) is only valid for PACS. For SPIRE and HIFI only relative knowledge w.r.t. PACS is required (HERS-0650), which means the LOS can be optimised for PACS. Independent adjustment of LOS and pupil mismatch is achieved by separate lateral and angular (to a certain degree) adjustment of Telescope and OB.

5 Alignment Plan

This chapter defines the alignment philosophy and the measurements which will be performed with the individual models. During the on-ground alignment two constraints must be taken into account:

1. The alignment requirements are valid for in-orbit conditions

2. The alignment requirements are specified for operational conditions, whereas the alignment can only be performed at ambient conditions.

The following environmental conditions will change between on-ground alignment and in-orbit operation:

- Gravity from 1g to zero g
- Atmospheric pressure from 1bar to 0bar
- Outer CVV and telescope support structure temperature

These effects must be determined and have to be pre-compensated by a corresponding offset on-ground.

In addition, launch loads such as vibration, acoustic noise and shock level have to be considered in the alignment budget.

For the initial alignment performed with the EQM and STM this offset must be determined theoretically and confirmed during testing (only in case of non negligible contribution).

Effects due to temperature and pressure change can be confirmed during on-ground testing, however, the gravity release effect can only be determined theoretically. Restrictions must also be made for the testing of the temperature change (on-ground→in-orbit): The shrinkage of the CVV will be verified during TB/TV testing with the HIFI Alignment Camera. The expected CVV temperature during TB/TV testing is appr. 80-90K. In orbit the expected CVV temperature is expected to be appr. 70K. For the residual 10 to 20K temperature difference the shrinkage will be verified by extrapolation.

An alignment check will be performed after the evacuation in order to quantify changes due to evacuation. Further alignment checks will be performed after cool down during the re-adjustment of the tank straps (the re-adjustment of the tank strap will move the OB) and before and after environmental testing.

Alignment of the Herschel PLM has to be performed in various steps.

5.1 EQM Alignment

With the EQM the alignment procedure shall be verified at an early stage of the AIV programme. The effect on alignment due to pressure change and cool down will also be determined as far as possible. The effect on alignment due to outer CVV temperature change can only be verified with the STM inside the TV chamber and use of the HIFI Alignment Camera. The test sequence for the EQM (concerning alignment) is as follows:

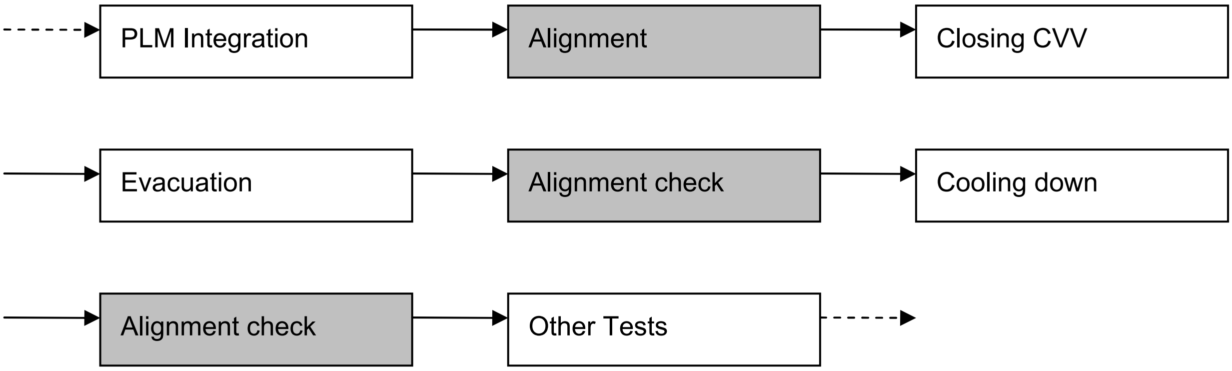


Figure 5.1-1: EQM Alignment Sequence

Only the alignment relevant steps have been shown. The complete test plan is shown in the relevant AIV documentation [RD 5].

The main tasks are the following:

- Early verification of the alignment as far as possible (mainly related to LOU alignment, no telescope on EQM)
- Verification of pressure and temperature change effects on alignment (with an outer CVV temperature at 300K)
- Lessons learned with the EQM can already be applied for the STM
- Risk reduction for the STM and FM programme

The EQM uses the ISO QM cryostat which will be modified to represent the Herschel cryostat as much as possible.

5.2 STM Alignment

The STM serves for the qualification of the structure. Therefore the alignment shall be checked before and after the environmental testing. Furthermore, the effect on alignment due to outer CVV temperature change shall be verified with the STM inside the TV chamber. For this test the Instrument and LOU MTDs will be used, equipped with alignment references at the same place as the Instrument FMs.

The main tasks are as follows:

- Qualification of the structure
  (Alignment measurement before and after the environmental tests)
- Verification of CVV shrinkage due to the temperature change w.r.t. outer CVV temperature inside TV chamber using the HIFI Alignment Camera
- Confirmation of the mathematical model

The actual test sequence is as follows (only alignment related steps have been shown). The complete test plan is shown in the relevant AIV documentation [RD 6]:

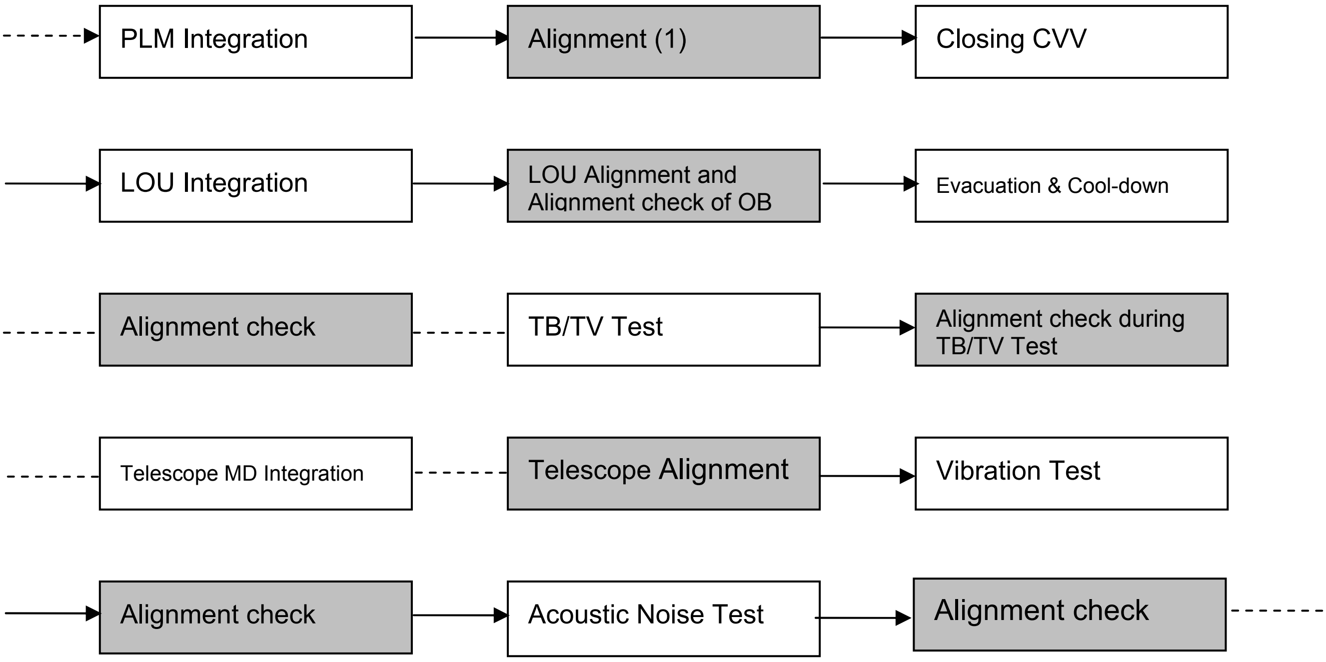


Figure 5.2-1: STM Alignment Sequence

1) Only OB and FPUs. See chapter 4 for the individual alignment steps

The most critical alignment of LOU w.r.t. the HIFI FPU will be monitored inside the TV chamber at nearly operational conditions. For this purpose two alignment cameras are mounted temporarily on the LOU allowing to monitor simultaneously tilt and offsets (two cameras are needed to determine the rotation about the y axis).

5.3 PFM Alignment

For the PFM a validated and accepted alignment procedure is already approved with the EQM and the STM. With the PFM the acceptance tests will be performed according to the following schema (only alignment relevant part). The complete test plan is shown in the relevant AIV documentation [RD 7]:

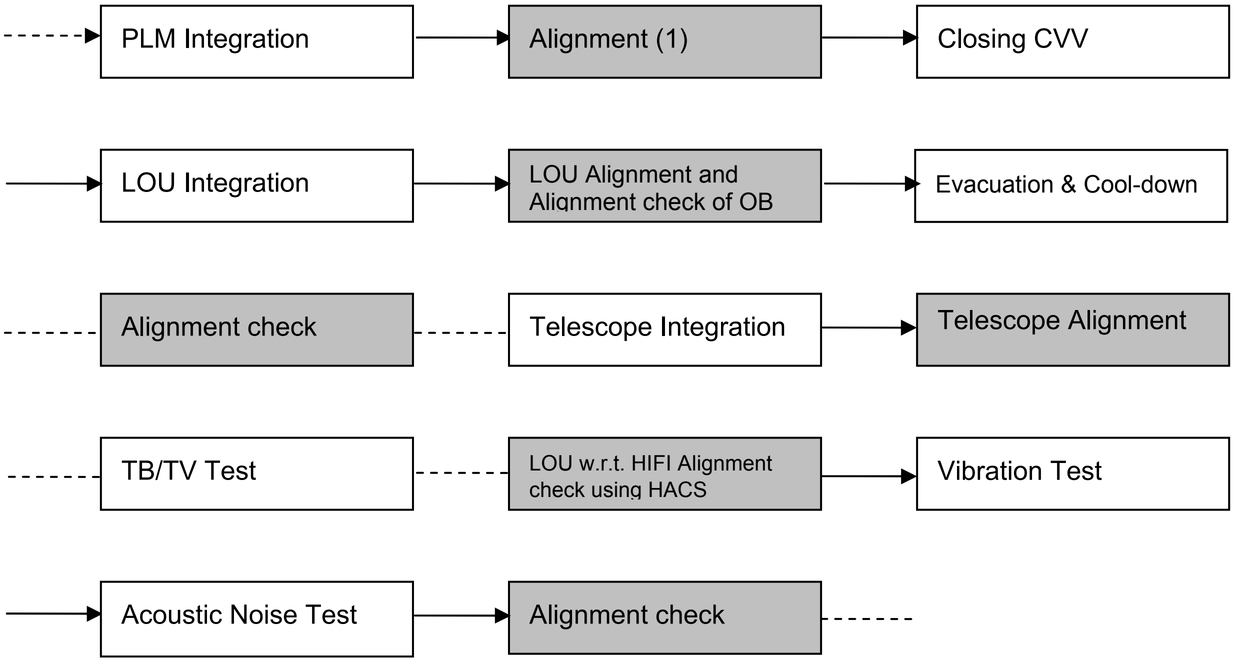


Figure 5.3-1: PFM Alignment Sequence

1) Only OB and FPUs. See chapter 4 for the individual alignment steps

To ensure that the alignment requirements are achieved at nearly operational conditions two alignment check s are planned during TB/TV testing. With both tests the shrinking of the CVV will be confirmed and therefore the confidence of the FEM increased.
The following tests are planned with the PFM during TB/TV testing:

- Verification of LOU w.r.t. HIFI FPU alignment using the HIFI Alignment Camera System (HACS).
- Verification of the Telescope cool-down behaviour w.r.t. the LOU.

This will be achieved by measuring the displacement between the Telescope M1 and the LOU using Videogrammetry method at ambient and after cool-down as described on page28.

Please note, that this test is not an end to end test, because the telescope is aligned to the instruments. But it can be compared to FEM results and increase the confidence of this model.

6 PLM Alignment Budget

In the previous chapters a Herschel alignment concept has been described for distance and angular measurements. In this chapter it shall be shown which individual errors contribute to the overall achievable alignment accuracy and which alignment accuracy can be achieved with the proposed alignment method. The result will be compared with the alignment requirements shown in chapter 3.

The following main error sources have been identified as contributions to the overall alignment error:

- On-Ground Alignment
  The achievable on-ground accuracy includes all measurement and adjustment errors occurring during on-ground integration and alignment procedures. The instruments internal alignment accuracy is under responsibility of the instrument manufacturer. The same is valid for the telescope

- Vacuum and Temperature effects
  Comprises all errors that will occur during cryostat evacuation and cool-down.

- In-Orbit and setting effects
  Includes all error sources originating from the launch loads and the differences between the on-ground alignment conditions and the in-orbit environmental conditions. The following error sources will be considered:

    - Gravity release
    - Atmospheric pressure from 1bar to 0bar
    - Initial temperature change (outer CVV temperature)
    - Mechanical environmental impact such as shock level, vibration and acoustic noise

- Thermoelastic distortion
  Covers the drift errors in-orbit as calculated with the load cases LC1 through LC3 (see next page).

For the CDR the alignment budget has been updated based on a thermal mechanical model (FEM) which considers the above mentioned effects besides the achievable on-ground alignment accuracy. The FEM (see [RD-2] and [RD-3]) is based on temperature maps for 3 load cases as defined by Alcatel LC1 through LC3.

The following Load cases has been calculated with the steady state model:

- LC 1 Summer solstice, SAA 90-30 deg
- LC 2 Summer solstice, SAA 90 deg
- LC 3 Summer solstice, SAA 90+30 deg

Additional load cases have been calculated in order to determine the gravity and pressure release for in-orbit conditions.

- LC 4 Ground Case (Cryostat cool down):
  CVV and SVM at ambient (293K), HTT at 1.8K
- LC 5 TB/TV Test Case:
  HSS and SVM at ambient (293K), HTT at 1.8K
  CVV +/- Radiators at 65K
  Radiative environment at 80K
- LC 6 1g gravity load in x direction (static and dynamic FEM model without SVM)
- LC 7 1 bar pressure load on CVV (Thermal distortion FEM model)
- LC 8 Waveguide forces on LOU due to thermal loads of waveguides (Thermal distortion FEM model)

Please note: The FEM analysis does not consider telescope and instrument internal stabilities and shrinking effects.
The HEPLM FEM includes a telescope FEM, however, only with one temperature for each of the above mentioned load cases (no temperature fields for telescope available). Instrument models are not available and therefore the HEPLM FEM does not show instrument internal thermal distortion effects. Therefore only one point for each instrument is reflected in the FEM analysis.

For more details please refer to [RD 2] and [RD 3].

6.1 Budget Results

The results are reflected in the following tables for each instrument separately and also for the axial and the lateral alignment (pupil mismatch). The LOU w.r.t. the HIFI FPU alignment results are provided in a separate table. For each alignment requirement the achievable value is compared with the requirement.

The overall alignment error has been classified in error classes marked with u (uncertainty e.g. measurement error), b (bias error) and t (thermoelastic distortion).

A bias error is a fixed offset error which is stable throughout the Herschel mission. Uncertainty errors are random errors and vary in an unpredictable manner.

In each error class rss summation has been applied. For the in-orbit changes (thermoelastic distortion) the difference of LC1 and LC2 (worst case) has been calculated. For the total error, linear summation of uncertainty, bias and thermoelastic distortion has been applied. The results shown have been calculated for a confidence level of 95% as agreed during the HOWG meeting dated 11.03.02.

The values presented in the following tables should be understood as achievable values and not as worst case. No margin has been added. The margin is the remaining difference between the achievable value and the requirement. All values are ± values if not stated otherwise.

For the distance of the telescope secondary mirror M2 to the focus we used 2638mm.

The shift of the OB w.r.t. the CVV due to cool down and the shrinkage of the CVV will be pre-compensated by a corresponding offset on-ground and do not contribute to the alignment budget shown in the tables. The following offset is expected (FEM Analysis) between on-ground alignment and in-orbit conditions.

	X [mm]	Y [mm]	Z [mm]	Rx [arcsec]	Ry [arcsec]	Rz [arcsec]
Instrument entrance w.r.t. Telescope Focus	1.77			1.5	2.2	0.8
Pupil Mismatch		1)	1)			
LOU w.r.t. HIFI FPU	1,17	2.20	0.62	10.0	0.89	59.1

1) Compensated by instrument cold→warm I/F dimensions w.r.t. OB

Only an adjustment offset remains, which is included in the budget and the shrinking uncertainty (5% of the absolute value).

All other bias values have been addressed as unsigned bias and rss summation has been applied.

The instrument and telescope internal alignment have been provided by the instrument and telescope manufacturer.

6.1.1 Instrument w.r.t. Telescope Alignment

See following pages.

Axial Alignment Budget PACS (Instrument w.r.t. Telescope Focus)

No.	Item	Error Class	X [mm]	Rx [arcsec]	Remark
1	**On-ground alignment (No. 2 to 9)**				
2	Instrument internal alignment w.r.t. instrument reference cube / mounting I/F	t u b	0.1 1.0 0		Instrument manufacturer responsibility TBC by PACS
3	Telescope internal alignment w.r.t. telescope reference cube / mounting I/F	t u 2) b 1)	1) 4.3		Telescope manufacturer responsibility TBC by ASEF
4	Measurement instrument w.r.t. CVV				
5	Measurement error on instrument cube	u	0.4	20	
6	Measurement error on CVV cube	u	0.4	20	
7	Measurement telescope w.r.t. CVV				
8	Measurement error on telescope cube	u	0.4	20	
9	Measurement error on CVV cube	u	0.4	20	
10	**Optical Bench**				
11	Flatness	b	0.05		According to specification
12	Stability	b	0.05		Due to cool down
	Instrument mounting accuracy	b		44.8	
13	**Tank Straps**	u	0.16	37.2	Scattering of material properties
14	**Shrinking uncertainty**				
15	OB w.r.t. CVV	u	0.30		5% of absolute value
16	Telescope w.r.t. CVV	u	0.40		5% of absolute value
17	**Setting effects**				
18	due to Launch	u	0.05		
19	due to TB/TV testing	u	0.05	12.4	
20	**Remaining adjustment offset**	b	0.4	20	
21	**In-orbit effects**				
22	Gravity release	b	0.10	1.1	
23	Pressure release	b	0.14	0.40	

24	Thermoelastic distortion				
25					
26	LC1-LC2	t	0.010	0.019	
27	**Total Error CVV**				
28	Uncertainty (rss)	u	0.96	56.0	
29	Bias (rss)	b	0.44	49.1	
30	Total including thermoelastic distortion (linear summation)		**1.4**	**105.1**	No. 28 plus No. 29 Plus No. 25
31	**Total Error PLM**				
32	Uncertainty (rss)	u	4.5	56.0	
33	Bias (rss)	b	0.45	49.1	
34	Total incl. thermoelastics		**5.1**	105.1	Instrument w.r.t. Tel. focus
35	**Requirement PLM**				
36	H-EPLM Requirement Specification		**7.0**		

1) The thermal stability is included in the bias value
2) In-orbit effects included

The requirement of 7.0 mm can be met with comfortable margin. The biggest contribution is coming from the telescope bias (4.3mm).

Lateral Alignment Budget PACS (Pupil Mismatch between Instrument and Telescope secondary)

No.	Item	Error Class	y,z [mm]	Ry,Rz [arcsec]	Remark
1	**On-ground alignment (No. 2 to 9)**				
2	Instrument internal alignment w.r.t. instrument reference cube / mounting I/F	t u b	0.1 0.5 0.5		Instrument manufacturer responsibility TBC by PACS
3	Telescope internal alignment w.r.t. telescope reference cube / mounting I/F	t u 2) b 1)	1) 1.14		Telescope manufacturer responsibility TBC by ASEF
4	Measurement instrument w.r.t. CVV				
5	Measurement error on instrument cube	u	0.4	20	
6	Measurement error on CVV cube	u	0.4	20	
7	Measurement telescope w.r.t. CVV				
8	Measurement error on telescope cube	u	0.4	20	
9	Measurement error on CVV cube	u	0.4	20	
10	**Optical Bench**				
	Flatness	b		34	According to specification Possible improvement by shims
	Stability	b	0.05	34	Due to cool down
	Instrument mounting accuracy	b	0.1		Dowel pin fixation
11	**Tank Straps**	u	0.16	24.8	Scattering of material properties
12	**Shrinking uncertainty**				
13	OB	u	0.21		5% of absolute value
14	Telescope w.r.t CVV	u	0.10		
15	**Setting effects**				
16	due to launch (vibration)				
17	due to TB/TV testing	u	0.05	12.4	
18	**Remaining adjustment offset**	b	0.3	20	
19					

20	**In-orbit effects**				
21	Gravity release	b	0.11	3)	
22	Pressure release	b	0.026	3)	
23	Thermoelastic distortion				
24					
25	LC1-LC2	t	0.0021		Contribution from Ry, Rz incl
26	**Total Error CVV**				
27	Uncertainty (rss)		0.85	48.7	
28	Uncertainty (rss) due to Ry, Rz		0.62		48.7arcsec ↔ 0.62mm
29	Uncertainty (rss) total		1.1		Contribution from Ry, Rz incl.
30	Bias (rss)		0.34	52.1	
31	Bias (rss) due to Ry, Rz		0.67		52.1arcsec ↔ 0.67mm
32	Bias (rss) total		0.75		Contribution from Ry, Rz incl.
33	Total including thermoelastic distortion (linear summation)		**1.8**		No. 29 plus No. 32 plus No. 25
34	Pupil Mismatch in M2 Plane		**2.5**		1.8 * SQRT(2) (half cone)
35	**Total Error PLM**				
36	Uncertainty (rss)		1.6		
37	Bias (rss)		0.91		
38	Total including thermoelastic distortion (linear summation)		2.6		
39	Pupil mismatch in M2 plane		**3.7**		2.6 * SQRT(2) (half cone)
40	**Requirement PLM**				
41	H-EPLM Requirement Specification		**7.0**		

1) The thermal stability is included in the bias value
2) In-orbit effects included
3) Included in y,z value

The requirement of 7.0mm can be met with comfortable margin. This improvement could be realised due to the better performance of the telescope (bias 1.14mm instead of 3mm).

Axial Alignment Budget SPIRE (Instrument w.r.t. Telescope Focus)

No.	Item	Error Class	X [mm]	Rx [arcsec]	Remark
1	**On-ground alignment (No. 2 to 9)**				
2	Instrument internal alignment w.r.t. instrument reference cube / mounting I/F	t u b	0.1 0.5 0		Instrument manufacturer responsibility TBC by SPIRE
3	Telescope internal alignment w.r.t. telescope reference cube / mounting I/F	t u 2) b 1)	1) 4.3		Telescope manufacturer responsibility TBC by ASEF
4	Measurement instrument w.r.t. CVV				
5	Measurement error on instrument cube	u	0.4	20	
6	Measurement error on CVV cube	u	0.4	20	
7	Measurement telescope w.r.t. CVV				
8	Measurement error on telescope cube	u	0.4	20	
9	Measurement error on CVV cube	u	0.4	20	
10	**Optical Bench**				
11	Flatness	b	0.05		According to specification
12	Stability	b	0.05		Due to cool down
	Instrument mounting accuracy	b		44.8	
13	**Tank Straps**	u	0.16	37.2	Scattering of material properties
14	**Shrinking uncertainty**				
15	OB w.r.t. CVV	u	0.30		5% of absolute value
16	Telescope w.r.t. CVV	u	0.40		5% of absolute value
17	**Setting effects**				
18	due to Launch	u	0.05		
19	due to TB/TV testing	u	0.05	12.4	
20	**Remaining adjustment offset**	b	0.4	20	
21	**In-orbit effects**				
22	Gravity release	b	0.11	1.3	
23	Pressure release	b	0.14	0.40	

24	Thermoelastic distortion				
25					
26	LC1-LC2	t	0.010	0.021	
27	**Total Error CVV**				
28	Uncertainty (rss)	u	0.96	56.0	
29	Bias (rss)	b	0.44	49.1	
30	Total including thermoelastic distortion (linear summation)		**1.4**	**105.1**	No. 28 plus No. 29 Plus No. 25
31	**Total Error PLM**				
32	Uncertainty (rss)	u	4.4	56.0	
33	Bias (rss)	b	0.45	49.1	
34	Total incl. thermoelastics		**5.0**	105.1	Instrument w.r.t. Tel. focus
35	**Requirement PLM**				
36	H-EPLM Requirement Specification		**7.7**		

1) The thermal stability is included in the bias value
2) In-orbit effects included

The requirement of 7.7mm can be met with comfortable margin. The biggest contribution is coming from the telescope bias (4.3mm).

Lateral Alignment Budget SPIRE (Pupil Mismatch between Instrument and Telescope secondary)

No.	Item	Error Class	y,z [mm]	Ry,Rz [arcsec]	Remark
1	**On-ground alignment (No. 2 to 9)**				
2	Instrument internal alignment w.r.t. instrument reference cube / mounting I/F	t u b	0.1 1.3 0		Instrument manufacturer responsibility TBC by SPIRE
3	Telescope internal alignment w.r.t. telescope reference cube / mounting I/F	t u 2) b 1)	1) 1.14		Telescope manufacturer responsibility TBC by SPIRE
4	Measurement instrument w.r.t. CVV				
5	Measurement error on instrument cube	u	0.4	20	
6	Measurement error on CVV cube	u	0.4	20	
7	Measurement telescope w.r.t. CVV				
8	Measurement error on telescope cube	u	0.4	20	
9	Measurement error on CVV cube	u	0.4	20	
10	**Optical Bench**				
	Flatness	b		34	According to specification Possible improvement by shims
	Stability	b	0.05	34	Due to cool down
	Instrument mounting accuracy	b	0.1		Dowel pin fixation
11	**Tank Straps**	u	0.16	24.8	Scattering of material properties
12	**Shrinking uncertainty**				
13	OB	u	0.21		5% of absolute value
14	Telescope w.r.t. CVV	u	0.10		
15	**Setting effects**				
16	due to launch (vibration)				
17	due to TB/TV testing	u	0.05	12.4	
18	**Remaining adjustment offset**	b	0.3	20	
19					

20	**In-orbit effects**				
21	Gravity release	b	0.12	3)	
22	Pressure release	b	0.027	3)	
23	Thermoelastic distortion				
24		t			
25	LC1-LC2	t	0.0028		Contribution from Ry, Rz incl
26	**Total Error CVV**				
27	Uncertainty (rss)		0.85	48.7	
28	Uncertainty (rss) due to Ry, Rz		0.62		48.7arcsec ↔ 0.62mm
29	Uncertainty (rss) total		1.1		Contribution from Ry, Rz incl.
30	Bias (rss)		0.34	52.1	
31	Bias (rss) due to Ry, Rz		0.67		52.1arcsec ↔ 0.67mm
32	Bias (rss) total		0.75		Contribution from Ry, Rz incl.
33	Total including thermoelastic distortion (linear summation)		**1.8**		No. 29 plus No. 32 plus No. 25
34	Pupil Mismatch in M2 Plane		**2.5**		1.8 * SQRT(2) (half cone)
35	**Total Error PLM**				
36	Uncertainty (rss)		2.0		
37	Bias (rss)		0.76		
38	Total including thermoelastic distortion (linear summation)		**2.9**		
39	Pupil mismatch in M2 plane		**4.1**		2.9 * SQRT(2) (half cone)
40	**Requirement PLM**				
41	H-EPLM Requirement Specification		**9.5**		

1) The thermal stability is included in the bias value
2) In-orbit effects included
3) Included in y,z value

The requirement of 9.5mm can be met with comfortable margin. This improvement could be realised due to the better performance of the telescope (bias 1.14mm instead of 3mm).

Axial Alignment Budget HIFI (Instrument w.r.t. Telescope Focus)

No.	Item	Error Class	X [mm]	Rx [arcsec]	Remark
1	**On-ground alignment (No. 2 to 9)**				
2	Instrument internal alignment w.r.t. instrument reference cube / mounting I/F	t u b	0.1 2.7 2.0		Instrument manufacturer responsibility TBC by HIFI
3	Telescope internal alignment w.r.t. telescope reference cube / mounting I/F	t u 2) b 1)	1) 4.3		Telescope manufacturer responsibility TBC by ASEF
4	Measurement instrument w.r.t. CVV				
5	Measurement error on instrument cube	u	0.4	20	
6	Measurement error on CVV cube	u	0.4	20	
7	Measurement telescope w.r.t. CVV				
8	Measurement error on telescope cube	u	0.4	20	
9	Measurement error on CVV cube	u	0.4	20	
10	**Optical Bench**				
11	Flatness	b	0.05		According to specification
12	Stability	b	0.05		Due to cool down
	Instrument mounting accuracy	b		44.8	
13	**Tank Straps**	u	0.16	37.2	Scattering of material properties
14	**Shrinking uncertainty**				
15	OB w.r.t. CVV	u	0.30		5% of absolute value
16	Telescope w.r.t. CVV	u	0.40		5% of absolute value
17	**Setting effects**				
18	due to Launch	u	0.05		
19	due to TB/TV testing	u	0.05	12.4	
20	**Remaining adjustment offset**	b	0.4	20	
21	**In-orbit effects**				
22	Gravity release	b	0.12	1.6	
23	Pressure release	b	0.14	0.40	

24	Thermoelastic distortion				
25					
26	LC1-LC2	t	0.010	0.020	
27	**Total Error CVV**				
28	Uncertainty (rss)	u	0.96	56.0	
29	Bias (rss)	b	0.44	49.1	
30	Total including thermoelastic distortion (linear summation)		**1.4**	**105.1**	No. 28 plus No. 29 Plus No. 25
31	**Total Error PLM**				
32	Uncertainty (rss)	u	5.2	56.0	
33	Bias (rss)	b	2.1	49.1	
34	Total incl. thermoelastics		**7.4**	105.1	Instrument w.r.t. Tel. focus
35	**Requirement PLM**				
36	H-EPLM Requirement Specification		**8.5**		
37	HIFI		**8.5**		HIFI E-Mail dated 24.05.02

1) The thermal stability is included in the bias value
2) In-orbit effects included

The requirement of 8.5mm can be met with sufficient margin. The biggest contribution is coming from the telescope bias (4.3mm) and the internal alignment error of HIFI itself (4.8mm).

Lateral Alignment Budget HIFI (Pupil Mismatch between Instrument and Telescope secondary)

No.	Item	Error Class	y,z [mm]	Ry,Rz [arcsec]	Remark
1	**On-ground alignment (No. 2 to 9)**				
2	Instrument internal alignment w.r.t. instrument reference cube / mounting I/F	t u b	0.1 10 1		Instrument manufacturer responsibility TBC by HIFI
3	Telescope internal alignment w.r.t. telescope reference cube / mounting I/F	t u 2) b 1)	1) 1.14		Telescope manufacturer responsibility TBC by ASEF
4	Measurement instrument w.r.t. CVV				
5	Measurement error on instrument cube	u	0.4	20	
6	Measurement error on CVV cube	u	0.4	20	
7	Measurement telescope w.r.t. CVV				
8	Measurement error on telescope cube	u	0.4	20	
9	Measurement error on CVV cube	u	0.4	20	
10	**Optical Bench**				
	Flatness	b		34	According to specification Possible improvement by shims
	Stability	b	0.05	34	Due to cool down
	Instrument mounting accuracy	b	0.1		Dowel pin fixation
11	**Tank Straps**	u	0.16	24.8	Scattering of material properties
12	**Shrinking uncertainty**				
13	OB	u	0.21		5% of absolute value
14	Telescope w.r.t. CVV	u	0.10		
15	**Setting effects**				
16	due to launch (vibration)				
17	due to TB/TV testing	u	0.05	12.4	
18	**Remaining adjustment offset**	b	0.3	20	
19					

20	**In-orbit effects**				
21	Gravity release	b	0.16	3)	
22	Pressure release	b	0.027	3)	
23	Thermoelastic distortion				
24		t			
25	LC1-LC2	t	0.0027		Contribution from Ry, Rz incl
26	**Total Error CVV**				
27	Uncertainty (rss)		0.85	48.7	
28	Uncertainty (rss) due to Ry, Rz		0.62		48.7arcsec ↔ 0.62mm
29	Uncertainty (rss) total		1.1		Contribution from Ry, Rz incl.
30	Bias (rss)		0.34	52.1	
31	Bias (rss) due to Ry, Rz		0.67		52.1arcsec ↔ 0.67mm
32	Bias (rss) total		0.75		Contribution from Ry, Rz incl.
33	Total Error including thermoelastic distortion (linear summation)		**1.8**		No. 28 plus No. 31 plus No. 24
34	Pupil Mismatch in M2 Plane		**2.5**		1.8 * SQRT(2) (half cone)
35	**Total Error PLM**				
36	Uncertainty		10.1		
37	Bias		1.3		
38	Total including thermoelasic		11.5		
39	**Pupil mismatch in M2 plane**		**16.3**		11.5 * SQRT(2) (half cone)
40	**Requirement**				
41	H-EPLM Requirement Specification		**24.0**		
42	HIFI		**24.0**		HIFI E-Mail dated 7.06.02

1) The thermal stability is included in the bias value
2) In-orbit effects included
3) Included in y,z value

The requirement of 24mm can be met with sufficient margin. The biggest contribution is coming from the internal alignment error of HIFI itself.

6.1.2 LOU alignment w.r.t. HIFI FPU Budget

No.	Item	Error Class	X[mm]	Y[mm]	Z[mm]	Rx [arcsec]	Ry [arcsec]	Rz [arcsec]	Remark
1	**On-ground alignment (No. 2 to 6)**								
2	HIFI internal alignment error w.r.t. HIFI alignment device								Instrument manufacturer responsibility 1)
3	LOU internal alignment error w.r.t.LOU reference cube								LOU manufacturer responsibility 1)
4	Measurement LOU w.r.t. HIFI	u	0.2	0.50	0.2	20	2)	20	Accuracy of HIFI Alignment Camera
5	Measurement error on HIFI alignment device	u							n.a. in case HIFI Alignment Camera is available
6	Measurement error on LOU alignment device	u							n.a. in case HIFI Alignment Camera is available
7	**Optical Bench**								
8	Flatness	b	0.03				15	20	At room temperature
9	Stability	b	0.05				25	34	During cool down
	Instrument mounting accuracy	b		0.1	0.1	44.8			
10	**Tank Straps**	u	0.16	0.16	0.16	37.2	24.8	24.8	Scattering of material properties
11	**Shrinking uncertainty**								
12	OB w.r.t. CVV	u	0.30	0.30	0.30				
13	LOU w.r.t. CVV	u	0.35	0.30	0.30	1.0	1.0	1.0	
14	**Setting effects**								

15	due to launch (vibration)								
No.	Item		X[mm]	Y[mm]	Z[mm]	Rx [arcsec]	Ry [arcsec]	Rz [arcsec]	Remark
16	due to TB/TV testing	u	0.05	0.05	0.05	12	12	12	
17	**In-orbit effects**								
18	Gravity release	b	0.010	0.007	0.033	14.3	0.91	33.4	
19	Pressure release	b	0.11	0.10	0.006	2.2	1.0	40.0	
20	Thermoelastic distortion								
21									
22	LC1-LC2	t	0.0074	0.0076	0.0038	0.070	0.16	0.10	
	Waveguide introduced distortion	b	0.008	0.001	0.001	0.30	0.30	1.7	
	Effect due to CVV Window Tilt	b	0.09						Due to Rz= +2°
23	**Total Error (Bias and Uncertainty)**								
24	Uncertainty (rss)		0.50	0.67	0.50	43.9	3)	34.1	
25	Uncertainty (rss) due to Ry						3)		
26	**Uncertainty (rss) total**		**0.50**	**0.67**	**0.50**	**43.9**		**34.1**	
27	Bias (rss)		0.15	0.14	0.11	47.1	28.9	65.4	
28	Bias (rss) due to Ry		0.046						
29	**Bias (rss) total**		**0.16**	**0.14**	**0.11**	**47.1**	**3)**	**65.4**	
30	**Total including thermoelastic distortion** (linear summation)		**0.67**	**0.81**	**0.61**	**91.0**	**3)**	**99.5**	No. 26 plus No. 29 plus 21 (22)
31	**Requirement**								
32	Alignment		0.75	15	0.75	136.8	3)	136.8	
33	Stability in 100 sec.		0.075	0.003	0.075	10.8	144	10.8	

1) The LOU w.r.t the HIFI FPU requirement is applicable from the LOU alignment device to the HIFI FPU alignment device and therefore the HIFI and LOU internal alignment do not contribute to this requirement.
2) Covered by displacement measurement in x direction
3) There is no requirement for Ry itself. The shift caused by Ry must be included in the displacement of the x direction.

All alignment requirements for the LOU w.r.t. the HIFI FPU can be met.
The most stringent requirement is the displacement in x direction. The achievable value is here 0.67mm in comparison to the requirement of 0.75mm, so only minor margin is left.

To assess the stability requirements we have compared the difference of LC1-LC2 which takes into account a change of the pitch from 0° to –30° und is the worst case. In y direction a stability of 0.0076mm for LC1-LC2 can be achieved, steady state analysis for an unlimited time interval which has to be compared with the **goal** of 0.003mm/100 sec. To assess this more detailed the following transient calculation has been performed.
The transient cool-down curve of the LOU Baseplate is shown in Figure 6.1.2-1 and [RD 8], chapter 7.3.3).

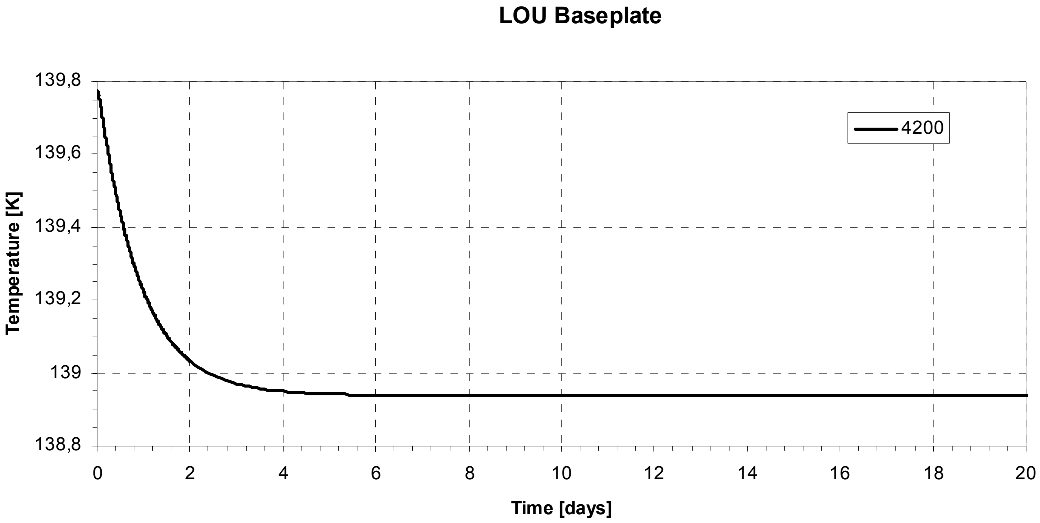


Figure 6.1.2-1: Transient Cool-Down of LOU Baseplate after S/C Rotation 30° about the y Axis

The temperature difference of the LOU baseplate for LC1-LC2 is 0.834K. The maximum gradient (Figure 6.1.1-1) is 1mK/100sec which leads to a stability of better than 0.00001mm/100sec. This value is much smaller than the goal of 0.003mm/100sec.

The achievable stability requirements in x and z direction are much better than required, already for steady state conditions. Therefore no transient calculations for x and z direction has been performed.

6.1.3 Line of Sight related Requirements

1. Alignment Bias of PACS LOS w.r.t. the PLM/SVM Interface frame (incl. ground and in-orbit effects) **HERS 0640**

No.	Item	Error Class	LOS [arcsec]	Remark
1	Gravity release	b	3.1	
2	Pressure release	b	1.5	
3	Impact on LOS due to flatness of OB	b	0.3	
4	Remaining OB adjustment offset	b	1.19	
5	Load Case 1	b	95.9	Defines worst case
6	**Total Bias error**	b	**95.9**	RSS (1-5)
7	Thermoelastic distortion LC1-LC2		0.21	In-orbit effect
8	**Total Error**		**96.1**	Lin. Sum (6-7)
9	**Requirement**	b	**300**	

The remaining OB adjustment offset (R) is the lateral remaining adjustment error w.r.t. the nominal position achieved after re-adjustment of the tank straps. The impact on LOS (Θ) is given by: tan Θ= R / F. The flatness of the OB leads to an additional angular deviation of the instrument. This introduces a lateral shift of the central image point within the system focal surface of the telescope. This lateral shift causes a change of the LOS.-

2. SPIRE and HIFI LOS knowledge w.r.t. PACS LOS (incl. on-ground alignment knowledge and in-orbit stability) **HERS 0650**

No.	Item	Error Class	y [mm]	z [mm]	Remark
1	Measurement uncertainty on PACS cube	u	0.4	0.4	Uncertainty for 68% is 0.2mm
2	Measurement uncertainty on SPIRE (HIFI) cube	u	0.4	0.4	
3	Shrinking uncertainty OB	u	0.21	0.21	
5	Thermoelastic distortion in-orbit for PACS	t	0.0021	0.0021	
6	Thermoelastic distortion in-orbit for SPIRE (HIFI)	t	0.0028	0.0028	
7	Total in-orbit uncertainty for the distance SPIRE (HIFI) entrance w.r.t. the PACS entrance	u	0.61	0.61	

			ΔRy [arcsec]	ΔRz [arcsec]	Remark
8	**HIFI LOS knowledge w.r.t. PACS LOS**		**4.4**	**4.8**	1)
9	**SPIRE LOS knowledge w.r.t. PACS LOS**		**4.4**	**5.9**	1)
10	**Achievable numbers: HIFI w.r.t. PACS** **SPIRE w.r.t. PACS**		**4.5** **4.5**	**5.0** **6.0**	As proposed by Alcatel 2)
11	**Requirement proposed by Astrium** **Hifi w.r.t. PACS** **SPIRE w.r.t. PACS**		 **6.6** **6.6**	 **7.2** **8.9**	Proposed by Astrium

1) The LOS has been calculated as follows: ΔRxi = xi/ f. (Difference between PACS and SPIRE (resp. HIFI).

xi: Distance between the Instrument entrance PACS w.r.t. SPIRE (resp. HIFI) in y and z direction
f: Focal length of the telescope (28350mm, min value)
Focal Length measurement accuracy: 90mm

Calculation according to [RD 9]

Distance between PACS and SPIRE FPU entrance: 169.3mm in z direction

Distance between PACS and HIFI FPU entrance: 79.4mm in z direction

Distance between PACS and SPIRE (HIFI) entrance: 0 in y direction

The values shown are achievable values without margin. To define acceptable requirements 50% margin has to be considered. No requirement defined at this time.

2) Achievable values proposed by Alcatel and discussed during the CDR RID disposition meeting 22./ 23.06.03. However, no margin provided by Alcatel. The achievable values calculated by Astrium (row 8 and 9) most likely can be achieved, but not guarenteed. Therefore, margin has to be applied and requirements have to be defined.

3. Around LOS alignment bias of each instrument w.r.t. the PLM/SVM interface frame (incl. groung and in-orbit effects) **HERS 0645**

No.	Item	Error Class	LOS [arcsec]	Remark
1	Gravity release	b	1.6	
2	Pressure release	b	0.57	
3	Instrument mounting Accuracy	b	45	
4	Remaining OB adjustment offset	b	20	
5	Load Case 3	b	4.7	Defines worst case
6	Setting effects	b	12.4	

7	**Total Bias error**	b	**51.0**	RSS (1-6)
8	Thermoelastic distortion	t	0.47	In-orbit effect (LC1-LC3 is worst case)
9	**Total Error**		**51.5**	Lin. Sum (7-8)
10	**Requirement**	b	**720**	

4. Around LOS alignment knowledge of each instrument w.r.t. the PLM/SVM interface frame (incl. on-ground alignment knowledge, in-orbit stability) **HERS 0660**

No.	Item	Error Class	Around LOS [arcsec]	Remark
1	Measurement error on instrument cube	u	10	68% confidence level
2	Measurement error on CVV cube	u	10	
3	Knowledge of PLM/SVM interface frame	u	15	
4	Total Uncertainty Error	u	20.6	(RSS)
5	Thermoelastic effect	t	0.47	Worst case given by LC1-LC3
6	**Total Error**		**21.1**	Lin. Sum (4-5)
7	**Requirement**		**30**	68% confidence level

5. Alignment stability during observation phase of instrument LOS w.r.t. the CVV/STR assembly interface plane **HERS 0700 b**

For the LOS stability calculation during the observation phase the difference of the Load Cases 1, 2 and 3 has been considered. The worst case is given by the difference LC1-LC2. For completeness all differences are shown.

Please note, that the differences shown in the following table are result of a steady state analysis and unlimited time intervals.

No.	Item	LC 1-LC2 [arcsec]	LC1-LC3 [arcsec]	LC2-LC3 [arcsec]	Remark
1	**PACS LOS stability**	**Ry=0.26** **Rz= 0.026** **R ≤ 0.00005/ 1 minute**	Ry=0.060 Rz=0.012	Ry=0.20 Rz=0.014	Worst case defined by LC1-LC2 steady state
2	**SPIRE LOS stability**	**Ry=0.26** **Rz=0.024** **R ≤ 0.00005/ 1 minute**	Ry=0.060 Rz=0.0084	Ry=0.20 Rz=0.016	
3	**HIFI LOS stability**	**Ry=0.26** **Rz=0.025** **R ≤ 0.00005/ 1 minute**	Ry=0.060 Rz=0.011	Ry=0.20 Rz=0.014	
4	**Requirements**	**Ry=0.4 arcsec over 1 month** **Rz=0.2 arcsec over 1 month** **± 0.1 arcsec around each axis on 1 minute**			0.25 arcsec goal 0.1 arcsec goal ± 0.02 arcsec goal

The requirements about Ry and Rz can be fulfilled with sufficient margin even with the steady state analysis. However, the requirement of ± 0.1 arcsec around each axis on 1 minute is not fulfilled for Ry for steady state. To assess this more detailed the following transient calculation has been performed.
The transient cool-down curve of the CVV is shown in Figure 6.1.3-1 and [RD 8], chapter 7.3.3).

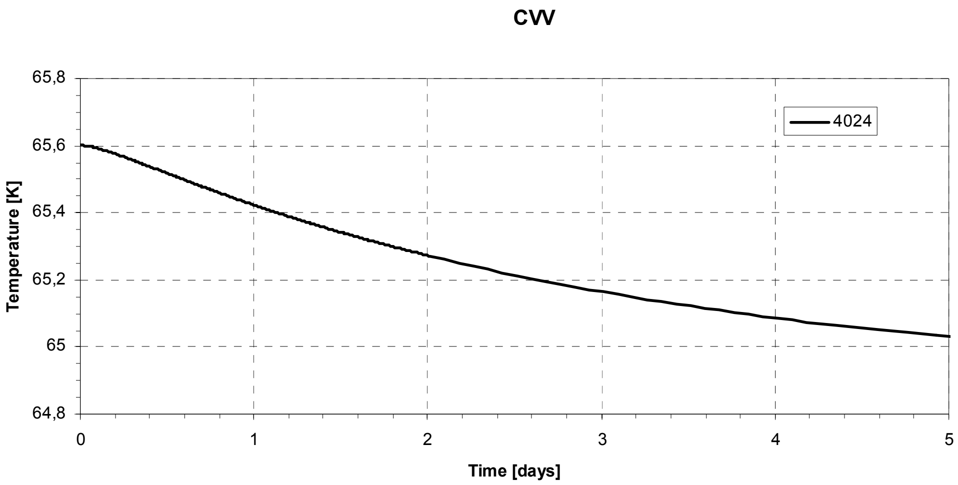


Figure 6.1.3-1: Transient Cool-Down of CVV after S/C Rotation 30° about the y Axis

The temperature difference of the CVV for LC1-LC2 is 0.765K. The maximum gradient (Figure 6.1.31-1) is 0.128mK/1min which leads to a stability of better than 0.00005arcsec/1min. This value is much smaller than the requirement of ± 0.1arcsec on 1 minute.

6. Alignment stability between CVV/STR assembly interface plane and the SVM/PLM interface plane between lift-off and operational mission (incl. launch and cool-down effects) **HERS 0702**

No.	Item	Rx [arcsec]	Ry [arcsec]	Rz [arcsec]	Remark
1	Gravity release	0.090	2.3	1.1	
2	Pressure release	0.16	1.0	0.034	
3	LC3-LC4	2.2	86.3	1.2	Considers difference between on-ground testing and in-orbit performance 1)
4	**Total Error**	**2.2**	**86.3**	**1.6**	
4	**Requirement**	**30 arcsec peak to peak**			

1) CVV and SVM at ambient (293K), HTT at 1.8K

For Rx and Rz this requirement can be fulfilled with comfortable margin. However, the stability requirement about the y axis of 30 arcsec is not achievable. The calculated value is 86.3arcsec. This is because the SVM is not symmetrically mounted w.r.t. the PLM and therefore different length of the 24 struts between SVM and PLM. There is no improvement possible and a dedicated RFD will be issued.

7. Alignment stability between CVV/STR assembly interface plane and SVM/PLM interface plane over one month during observation phase. **HERS 0704**

No.	Item	Rx [arcsec]	Ry [arcsec]	Rz [arcsec]	Remark
1	**Worst case of LCi-LCj**	**0.45**	**0.62**	**0.85**	
2	**Requirement**	**6 arcsec peak to peak over 1 month**			

7 Alignment Requirements at Subsystem Level

In this chapter the internal instrument and telescope alignment as defined by the manufacturers is listed and the alignment references for each instrument or H/W will be defined for which alignment is required.

The position of the alignment reference cubes is defined in the following sections. The accuracy of the reference cubes will be defined after agreement of the alignment requirements.
All alignment cubes (OB, CVV, Instruments and Telescope) must be equipped with cross hairs for linear distance measurements. The internal alignment must be referred to the cross hairs.
During environmental testing it shall be shown that the position of the reference cubes remain in a stable position within the required accuracy.

The visibility of the reference cubes during system level alignment is indicated by the surface normal in each direction.

7.1 Instruments

Each instrument has to be equipped with an external reference cube with cross hair representing its optical axis (position and direction). The positions proposed by the instruments have been checked.

To measure all relevant parameters, Rx, Ry, Rz, Tx, Ty, Tz, two sides of the reference cubes must be accessible as a minimum. The accessible and therefore used sides of the reference cubes during system level alignment will be defined by Astrium. The alignment cubes are visible during system level alignment from the directions as indicated in Figure 4-1 and Figure 7-1.

In order to minimise the alignment errors the same reference sides shall be used by the instruments for their internal alignment (no stringent requirement, but improves the overall performance).

The instrument internal alignment error is the deviation from the instrument reference point (or plane), to which the telescope has to be aligned, from the theoretical position. The instrument reference shall be known with respect to the instrument reference hole. The deviations shall be measured also w.r.t. the reference cube (only accessible during system level alignment). This error shall be defined as bias (offset), measurement uncertainty and thermoelastic distortion. The in-orbit effects shall be included. The values shall be defined for a confidence level of 95%.

The instruments shall be delivered together with a set of shimming plates. One set with nominal thickness and as a minimum a second oversized set that can be re-machined according to actual alignment needs.

7.1.1 HIFI

The HIFI FPU internal alignment error is defined as follows:

Focus direction (for the most critical mixer channel)

- Measurement accuracy ≤ ± 2.7mm
- Bias = 2.0
- Thermoelastic distortion ≤ ± 0.1mm

HIFI states that for the overall focus alignment 8.5mm is acceptable ([RD 10]).

Pupil Mismatch (in M2 plane**)**

- Measurement accuracy ≤ ± 10.0mm (each axis)
- Bias ≤ ± 1.0mm
- Thermoelastic distortion ≤ ± 0.1mm

HIFI states that for the overall pupil mismatch a half cone of 24.0mm is acceptable ([RD 11]).

The position of the reference cube is shown in Figure 4-1 and Figure 7-1.
The position of the alignment cube centre w.r.t. the OB coordinate system shall be:

x = 353.525mm	y = -116.5mm	z = 0mm

For the LOU alignment HIFI must be equipped with two additional alignment devices which shall be visible from -y side via two additional alignment windows adjacent to the first and last of the seven submillimeter windows, in position 0 and 8 (see Figure 4-1 and Figure 4-5).

For the LOU w.r.t. HIFI alignment the requirements are valid from FPU reference to LOU reference to cube and therefore the internal HIFI and LOU alignment must not be considered.

7.1.2 PACS

The PACS internal alignment error is defined as follows.

Focus direction

- Measurement accuracy ≤ ± 1.0mm
- Bias = 0
- Thermoelastic distortion ≤ ± 0.1mm

Pupil Mismatch (in M2 plane)

- Measurement accuracy ≤ ± 0.5mm
- Bias ≤ ± 0.5mm
- Thermoelastic distortion ≤ ± 0.1mm

The position of the reference cube is shown in Figure 4-1 and Figure 7-1.
The position of the alignment cube centre w.r.t. the OB coordinate system shall be:

x	y	z
x = 449.63mm	y = 119.14mm	z = 64.43

7.1.3 SPIRE

The SPIRE internal alignment error is defined as follows.

Focus direction

- Measurement accuracy ≤ ± 0.5mm
- Bias = 0
- Thermoelastic distortion ≤ ± 0.1mm

Pupil Mismatch (in M2 plane**)**

- Measurement accuracy ≤ ± 1.3mm
- Bias ≤ ± 0mm
- Thermoelastic distortion ≤ ± 0.1mm

The position of the reference cube is shown in Figure 4-1 and Figure 7-1.
The position of the alignment cube centre w.r.t. the OB coordinate system shall be:

x	y	z
x = 461.02mm	y = 110.0mm	z = -56.41mm

7.2 Optical Bench

The position of the OB reference cube has been defined together with the OB manufacturer. The position of the reference cube shall be measured with respect to the OB coordinate system. The position of the reference cube is shown in Figure 7-1.

7.3 Cryostat Vacuum Vessel

After integration of the OB into the cryostat the OB will be aligned w.r.t. the CVV. Therefore the CVV will be equipped with a reference cube mounted at the circumference of the CVV cylinders upper part. The CVV cube serves also as reference for the OB and the telescope accommodation after the cryostat cover has been closed. The cube faces represent the nominal direction of the telescope optical axis. For axial and lateral alignment they shall be equipped with cross hairs at known positions in CVV coordinates. A second redundant alignment cube will be mounted at the CVV as required. A second set of alignment cubes is mounted at the upper bulkhead. The position of the reference cubes is shown in Figure 7-2.

7.4 Telescope

After the cryostat has been closed the telescope can be integrated. For alignment w.r.t. the CVV cubes the telescope shall be equipped with a reference cube located nearby the interface triangle at a stable position. For axial and lateral alignment the reference cube must provide cross hairs.

In this report the following internal telescope alignment values have been used:

Focus direction

- Measurement accuracy: included in bias value
- Bias = 4.3mm
- Thermoelastic distortion: included in bias contribution

Pupil Decenter

- Measurement accuracy: included in bias value
- Bias ≤ ± 1.14mm
- Thermoelastic distortion: included in bias contribution.

These values have been agreed during the HOWG meeting, 11.06.02. They represent achievable values for the telescope internal alignment. They are not completely in line with the summation rule used in this report (bias includes uncertainty and thermoelastics) but the induced error is small.

The position of the telescope reference cubes is shown in Figure 7-3.

7.5 Alignment Windows

For the LOU alignment w.r.t. the HIFI FPU two alignment windows in the cryostat are needed. Suitable positions for these two windows would be adjacent to the first and last of the seven submillimeter windows, in position 0 and 8 (see Figure 4-5).

After the alignment activities these two windows shall be closed with a light-tight cover.

The alignment windows shall placed in the following positions:

- Window 1: x = 63mm z = 200mm
- Window 2: x = 63mm z = -200mm

The window diameter is 34mm.

No further alignment windows in the cryostat are needed with the proposed alignment concept.

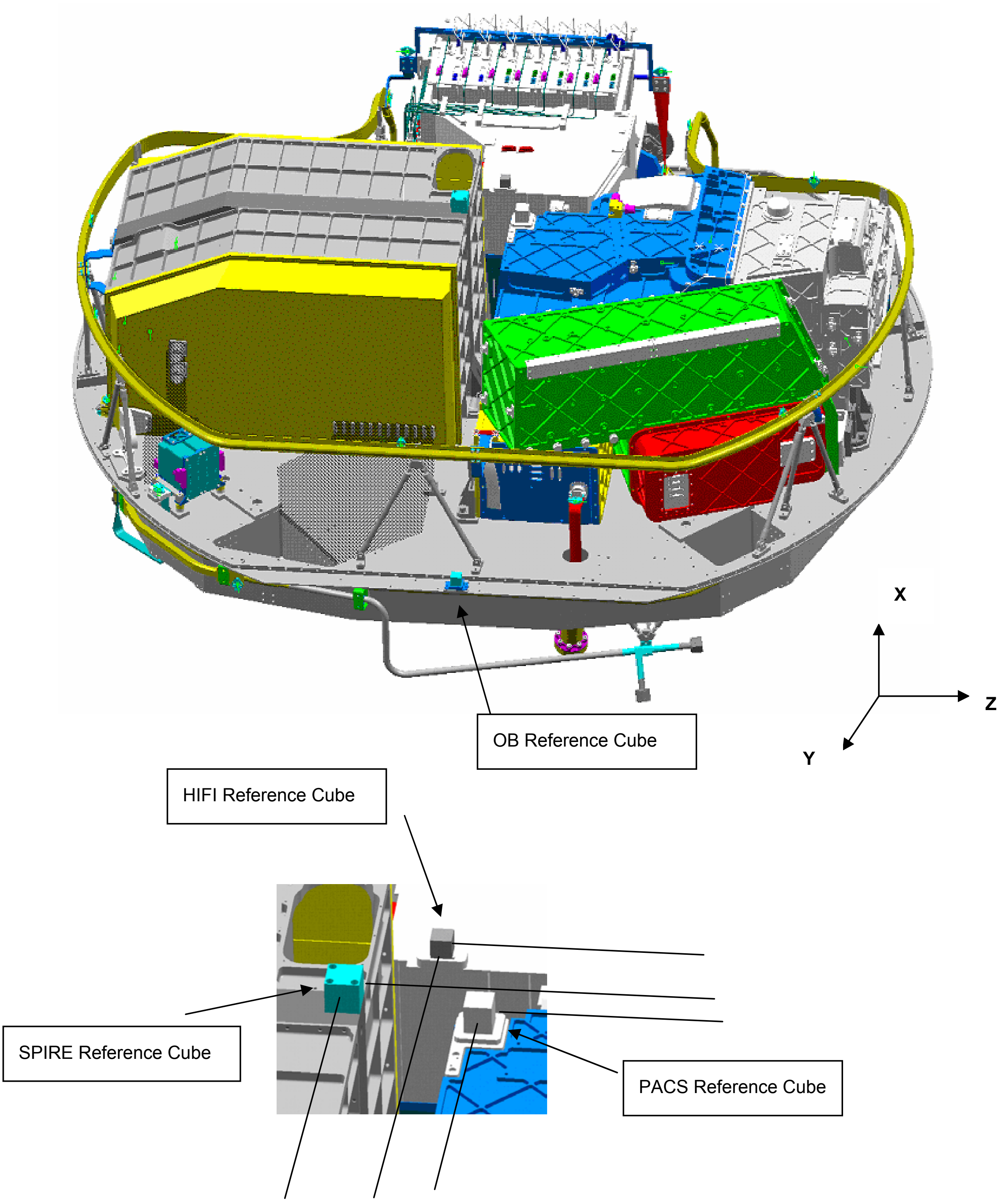


Figure 7-1: Reference cube position for OB and Instruments

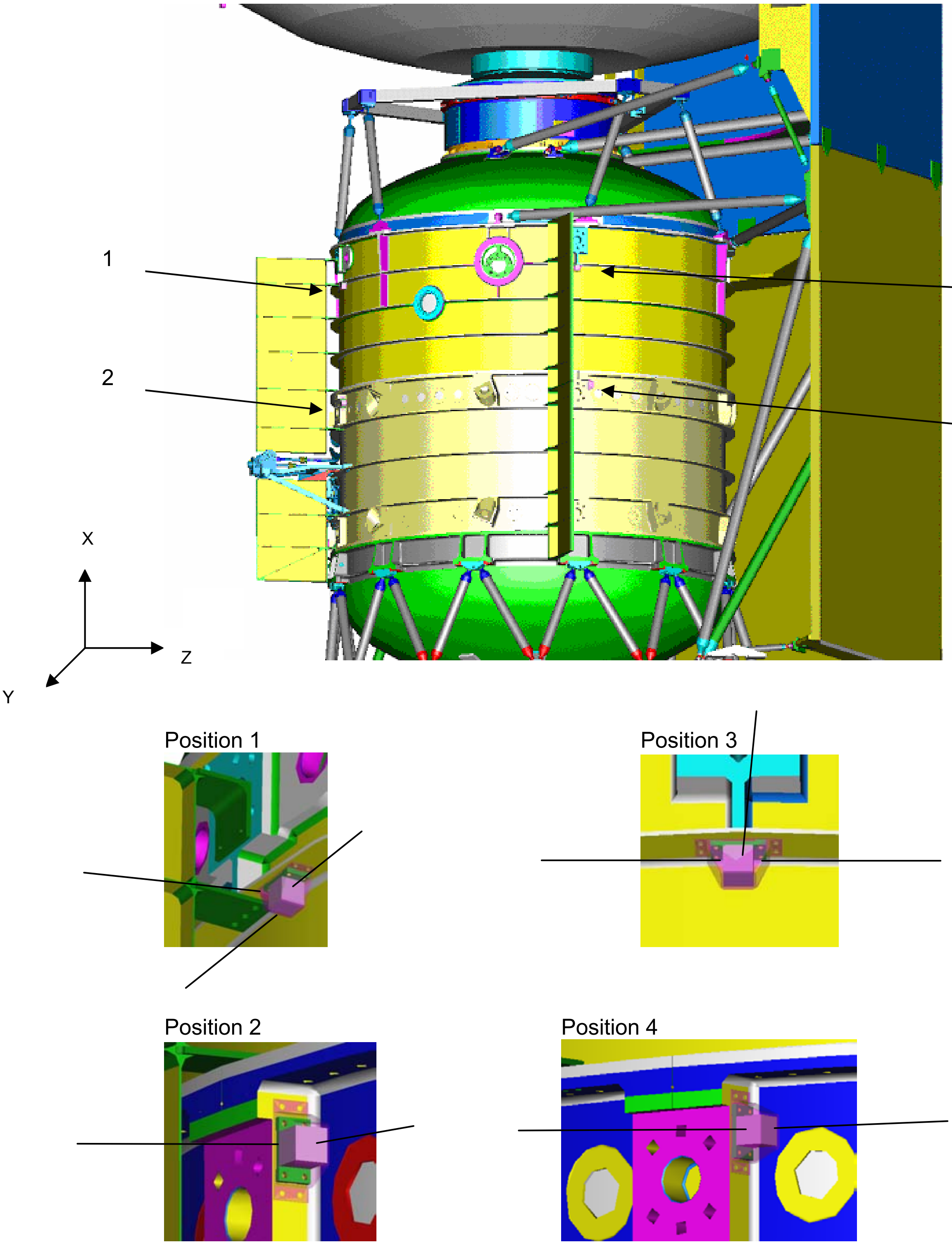


Figure 7-2: CVV Reference Cubes

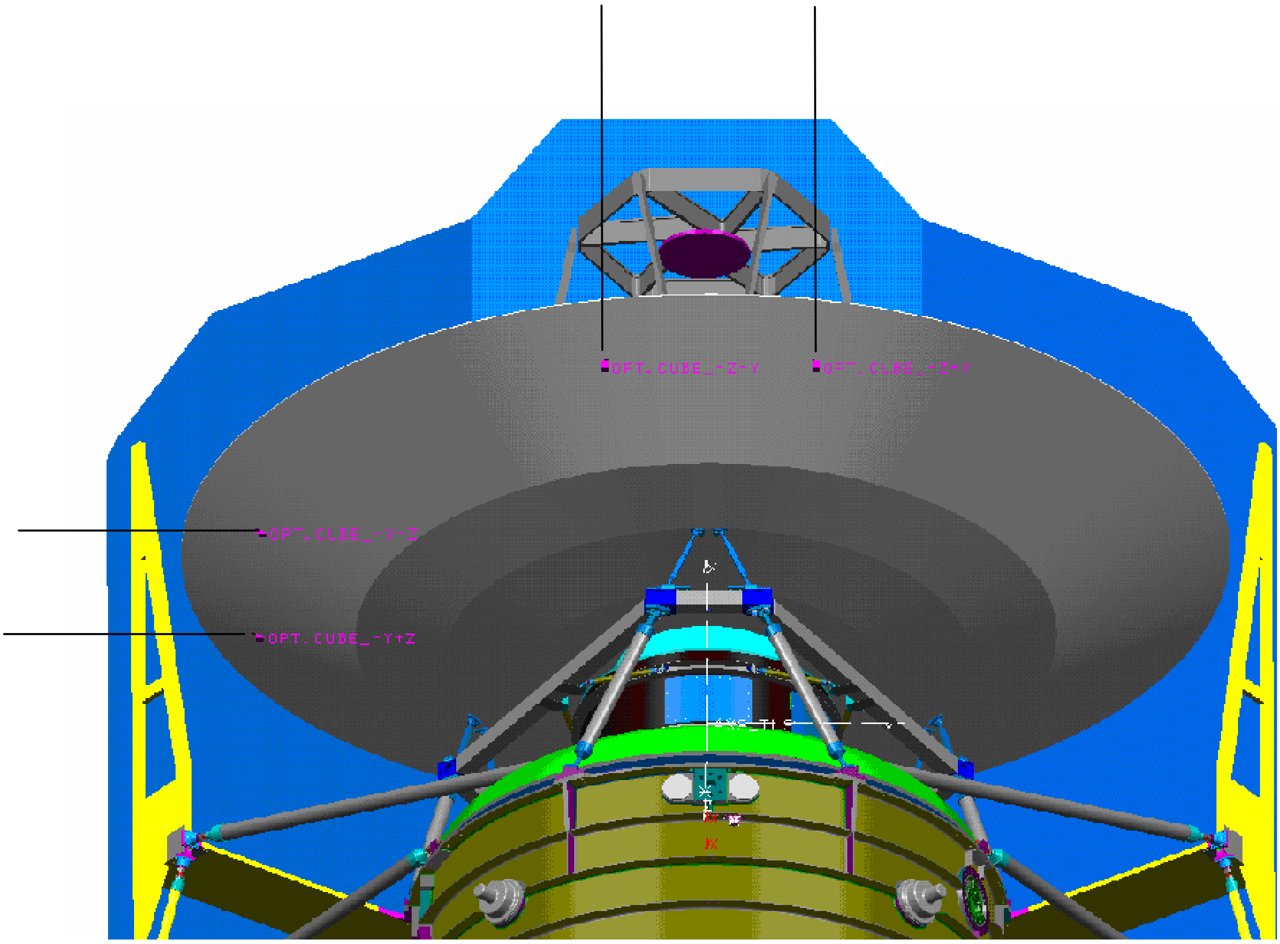


Figure 7-3: Telescope Reference Cubes

7.6 Alignment of Ventline Nozzles

In order to minimise the orbit disturbances due to helium exhaust, the Ventline Nozzles have to be aligned w.r.t. the satellite coordinate system.

The nozzle arrangement is shown in Figure 7.6-1.

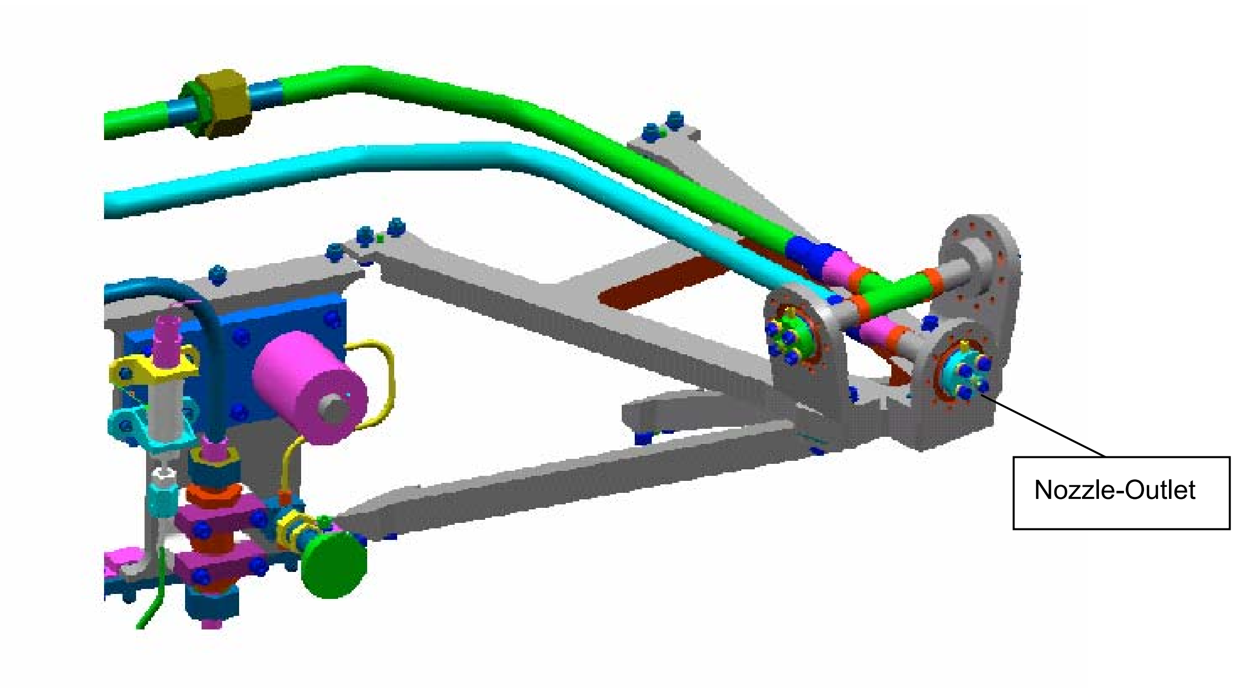


Figure 7.6-1: Arrangement of the three Ventline Nozzles

For the alignment a cover will be mounted at the nozzle-outlet. The cover carries an alignment cube which represents the nozzle direction. The cover with the alignment cube has to be delivered by the nozzle manufacturer.

The alignment requirement is ± 1 degree w.r.t. the y and z axes.

Aiming with a theodolite in autocollimation to the reference cube the nozzle direction can be determined and if necessary corrected with shimming plates located behind the nozzle-outlet.

8 Alignment Support Equipment

The alignment concept proposed above is chosen, that standard laboratory products can be used to a large extend. Most of the equipment is already available at Astrium, but needs to be adapted for Herschel. In the following table the main equipment needed for Herschel system level alignment activities is shown.

Nr.	Qty	Equipment	Description	Available	Procurement
1	2	Theodolite	Wild T2000 S or equivalent	x	
2	1	Linear Measurement Device	For axial and lateral distance measurements	x	
3	2	Angular Transfer Prism	As reference for azimuth	x	
4	2	HIFI Alignment Camera	LOU alignment monitoring		x
5		Alignment reference cubes	For OB, CVV......		x
6	1	Support Structure for LMD	For vertical and horizontal measurements	1)	
7	1	Tripod	For Theodolite Height appr. 7m		
8	1	Adjustable support for PLM or use of a rotary table	For precise levelling of the PLM		2)
9	1	Adapter	For SVM I/F		2)
10	1	Adapter	For PLM I/F		2)
11	1	Cherry Picker			2)

Table 8-1: Alignment Equipment List (preliminary)

1) Made with X95 System TBC

2) Will be procured with the MGSE Batch

9 Conclusion

In this report we have presented the Herschel alignment concept. The concept is based on conventional alignment tools except the HIFI Alignment Camera.

The alignment plan in chapter 5 describes the alignment relevant steps planned with the EQM, STM and PFM programme. The complete test plan is shown in the relevant AIV documentation.

The achievable error budget is presented in chapter 6 and compared to the requirements.
The most stringent requirements are for the LOU w.r.t. the HIFI FPU here especially in x direction. The achievable value in x direction is 0.67mm in comparison to the requirement of 0.75mm. In z direction 0.61mm can be achieved, the requirement is 0.75mm. The y direction is uncritical, 15mm are allowed.

For the instrument w.r.t. the telescope focus alignment PACS has the driving requirements. In x direction a value of 5.1mm is achievable. There is no problem compared to the requirement of 7.0mm. The biggest contribution is coming from the telescope with an uncertainty of 4.3mm.

The achievable value for SPIRE is 5.0mm in x direction. There is comfortable margin against the requirement of 7.7 mm.

For HIFI a value of 7.4mm is achievable in x direction with sufficient margin against the requirement of 8.5mm. HIFI states [RD 10] that the overall requirement for axial focus can be 8.5mm. Beside the big contribution of the telescope mentioned above the internal contribution of HIFI itself is 4.8mm.

For the lateral alignment (pupil mismatch in M2 plane) for PACS (3.7mm achievable) and SPIRE (4.1mm achievable) there is comfortable margin against the requirement of 7.0mm for PACS and 9.5mm for SPIRE. The achievable pupil mismatch for HIFI is 16.3mm. HIFI itself contributes to this value with 15.7mm. HIFI states that the requirement can be relaxed to 24mm half cone [RD 11] which gives sufficient margin on system level.

Please note that the values presented in this document have to be understood as achievable values on system level. No margin has been added. The margin is the remaining difference between the achievable value and the requirement.

The following tables summarise the achievable alignment results (all values are ±):

1: Instruments w.r.t. Telescope

	Focus Alignment (x mm)			Pupil Mismatch (lateral mm)		
	PACS	SPIRE	HIFI	PACS	SPIRE	HIFI
Achievable Value	5.1	5.0	7.4	3.7	4.1	16.3
Requirement	7.0	7.7	8.5	7.0	9.5	24.0

2: LOU w.r.t. HIFI Alignment

	Δx (mm)	Δy (mm)	Δz (mm)	Rx (arcsec)	Ry (arcsec)	Rz (arcsec)
Achievable Value	0.67	0.83	0.61	91.0	Incl. in x	99.5
Requirement	0.75	15.0	0.75	137	Incl. in x	137

LOU w.r.t. HIFI Stability

	Δx (mm)	Δy (mm)	Δz (mm)	Rx (arcsec)	Ry (arcsec)	Rz (arcsec)
Achievable Value 1)	0.0074	0.00001	0.0038	0.070	0.16	0.10
Requirement 2)	0.075	0.003	0.075	10.8	144	10.8

1) Calculated for LC1-LC2 steady state analysis, except for Δy where a transient calculation has been performed (see page 50)
2) Within 100sec. The very high stability along the y axis should be regarded as a goal (according to HIFI IID-B)

3: Line of Sight related Requirements

	Requirement	Achievable Value	Remark
PACS LOS w.r.t. PLM SVM I/F	5 arcmin	96.1 arcsec	Bias
Around LOS Instrument w.r.t. PLM /SVM I/F	12 arcmin	51.5 arcsec	Bias
Around LOS Instrument w.r.t. PLM /SVM I/F	0.5 arcmin	21.1 arcsec	Knowledge 1б value
SPIRE & HIFI LOS w.r.t. PACS LOS	To be defined 1)	Ry Rz SPIRE 4.4 5.9 HIFI 4.4 4.8	Knowledge Values in arcsec
LOS stability w.r.t. CVV/STR I/F plane	0.4 arcsec, y, 1month pp 0.2 arcsec, z, 1month pp ±0.1 arcsec, all, 1min	Ry= 0.26 arcsec Rz= 0.026 arcsec R ≤ 0,00005 arcsec	0.25 arcsec goal 0.1 arcsec goal ±0.02 arcsec goal
CVV/STR I/F plane w.r.t. SVM /PLM I/F plane Stability	30 arcsec , each axis pp	Rx= 2.2 arcsec **Ry= 86.3 arcsec** 2) Rz= 1.6 arcsec	Incl. all effects between lift-off and operational mission
CVV/STR I/F plane w.r.t. SVM /PLM I/F plane Stability	6 arcsec, each axis, 1month	Rx= 0.45 arcsec Ry= 0.62 arcsec Rz= 0.85 arcsec	During observation phase

1) No requirements defined at this time. For more information please see page 57.
2) Requirement of 30 arcsec not achievable for Ry. RFD to be issued

10 Abbreviations

AD	Applicable Document
AIV	Assembly Integration Verification
CVV	Cryostat Vacuum Vessel
EQM	Engineering Qualification Model
FPU	Focal Plane Unit
HIFI	Heterodyne Instrument for FIRST
IID A	Instrument Interface Document (Part A)
IID B	Instrument Interface Document (Part B)
HACS	HIFI Alignment Camera System
HOWG	Herschel Optical Working Group
H/W	Hardware
I/F	Interface
LOU	Local Oscillator Unit
LMD	Linear Measurement Device
MTD	Mass Thermal Dummy (for Instrument)
OB	Optical Bench
OGSE	Optical Ground Support Equipment
PACS	Photoconductor Array Camera & Spectrometer
PFM	Proto Flight Model
PLM	Payload Module
RD	Reference Document
S/C	Spacecraft
SPIRE	Spectral & Photometric Imaging Receiver
SS	Summer Solstice
STM	Structural Thermal Model
TM	Thermal Model
STR	Star Tracker
TBC	To Be Confirmed
TBD	To Be Determined
WS	Winter Solstice

	Name	Dep./Comp.		Name	Dep./Comp.
x	Alberti von Mathias Dr.	AOE22			
	Barlage Bernhard	AED11			
x	Bayer Thomas	AET52			
	Fehringer Alexander	AOE13			
	Gerner Willi	AED11			
	Grasl Andreas	OTN/AET52			
	Grasshoff Brigitte	AET12			
x	Hauser Armin	AOE23			
	Hendry David	Terma Resid.			
	Hinger Jürgen	AOE22	x	Alcatel	ASP
x	Hohn Rüdiger	AET52	x	ESA/ESTEC	ESA
	Huber Johann	AOA4			
	Hund Walter	ASE4A		**Instruments:**	
x	Idler Siegmund	AED432	x	MPE (PACS)	MPE
x	Ivády von András	FAE22	x	RAL (SPIRE)	RAL
x	Jahn Gerd Dr.	AOE23	x	SRON (HIFI)	SRON
	Kalde Clemens	APE3			
	Kameter Rudolf	OTN/AET52		**Subcontractors:**	
	Kettner Bernhard	AET42		Air Liquide, Space Department	AIR
	Knoblauch August	AET32		Air Liquide, Space Department	AIRS
	Koelle Markus	AET22		Air Liquide, Orbital System	AIRT
x	Kroeker Jürgen	AED65		Alcatel Bell Space	ABSP
	Kunz Oliver Dr.	AOE23		Astrium Sub-Subsyst. & Equipment	ASSE
	Lamprecht Ernst	OTN/ASI21		Austrian Aerospace	AAE
	Lang Jürgen	ASE4A		Austrian Aerospace	AAEM
x	Langfermann Michael	AET52		APCO Technologies S. A.	APCO
	Mack Paul	OTN/AET52		Bieri Engineering B. V.	BIER
x	Pastorino Michel	ASPI Resid.		BOC Edwards	BOCE
x	Peltz Heinz-Willi	AOE13		Dutch Space Solar Arrays	DSSA
	Pietroboni Karin	AED65		EADS CASA Espacio	CASA
	Platzer Wilhelm	AED22		EADS CASA Espacio	ECAS
x	Rebholz Reinhold	AET52		EADS Space Transportation	ASIP
	Reuß Friedhelm	AED62		Eurocopter	ECD
x	Rühe Wolfgang	AED65		HTS AG Zürich	HTSZ
	Runge Axel	OTN/AET52		Linde	LIND
	Sachsse Bernt	AED21		Patria New Technologies Oy	PANT
x	Schink Dietmar	AED422		Phoenix, Volkmarsen	PHOE
x	Schlosser Christian	OTN/AET52		Prototech AS	PROT
	Schmidt Rudolf	FAE22		QMC Instruments Ltd.	QMC
x	Schweickert Gunn	AOE22		Rembe, Brilon	REMB
	Steininger Eric	AED422		Rosemount Aerospace GmbH	ROSE
x	Stritter Rene	AED11		RYMSA, Radiación y Microondas S.A.	RYM
x	Tenhaeff Dieter	AOE22		SENER Ingenieria SA	SEN
	Thörmer Klaus-Horst Dr.	OTN/AED65		Stöhr, Königsbrunn	STOE
	Wagner Klaus	AOE23		Terma A/S, Herlev	TER
x	Wietbrock Walter	AET12			
x	Wöhler Hans	AOE22			

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