SPIRE-AST-DOC-000981

Title: **Herschel Alignment Concept**

CI-No:

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Project Management:	W. Rühe		17.06.02

Distribution: See Distribution List

Issue	Date	Sheet	Description of Change	Release
Draft 1	12.07.01	All	Draft Version	
Issue 1	24.05.02	All	First formal issue	
Issue 2	14.06.02	All	Changes according to HOWG meeting, dated 11.06.02	

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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.

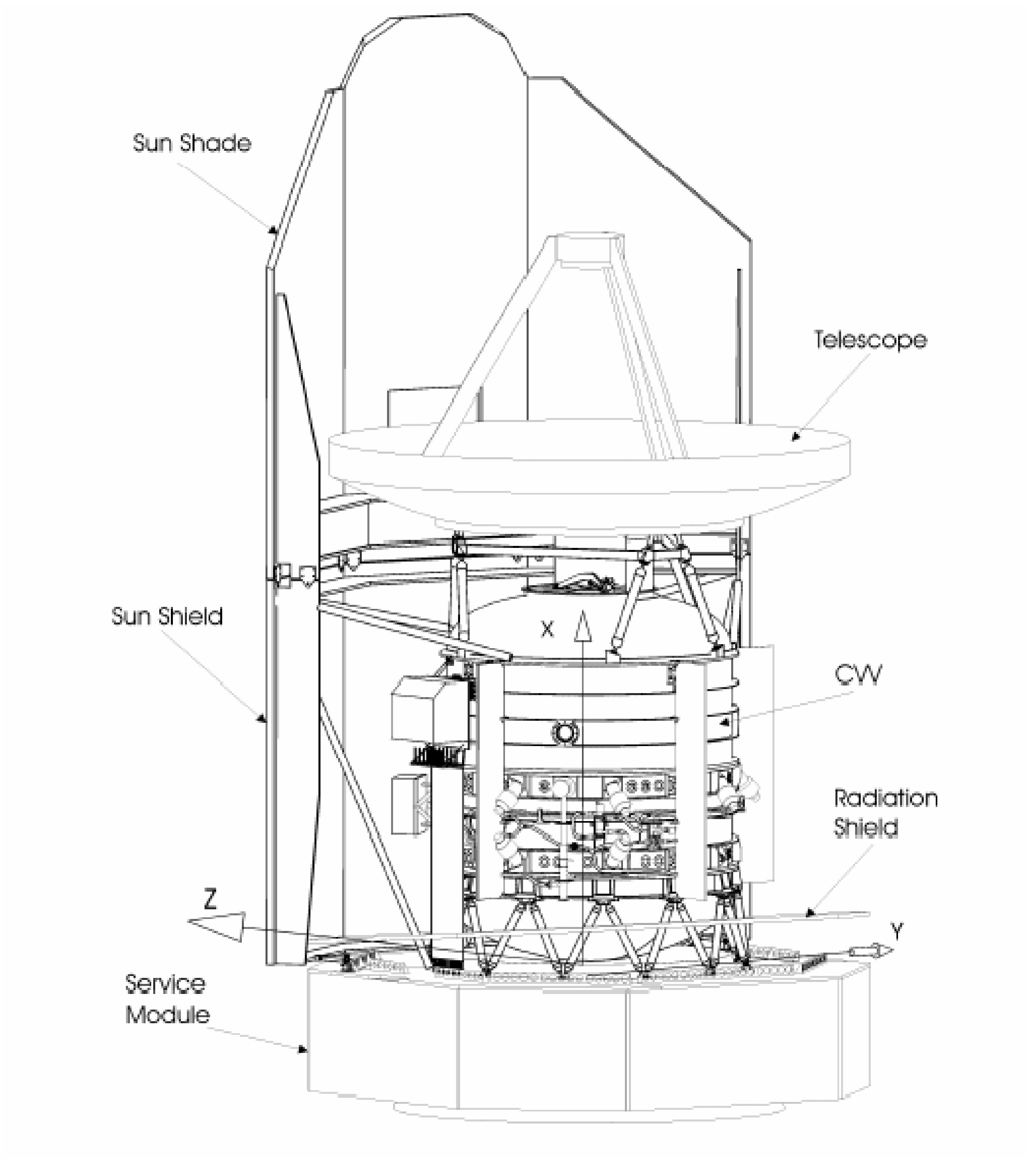


Figure 1-1: Herschel Satellite

2 Documents

2.1 Applicable Documents

[AD 1]	Instrument Interface Document IID Part A SCI-PT-IIDA-04624, Issue 2/0
[AD 2]	Instrument Interface Document Part B, Instrument HIFI SCI-PT-IIDB/HIFI-02125, Issue 2/0
[AD 3]	Instrument Interface Document Part B, Instrument PACS SCI-PT-IIDB/HIFI-02126, Issue 2/0
[AD 4]	Instrument Interface Document Part B, Instrument SPIRE SCI-PT-IIDB/HIFI-02124, Issue 2/0
[AD 5]	FIRST Telescope Specification SCI-PT-RS-04671, Issue 4/0

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

3 Alignment Requirements

The alignment requirements for Herschel are defined in the documents [AD 1] through [AD 4]. 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 (FPU at appr. 15K and LOU at appr. 100K), 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 as follows:

3.1 Axial Focus Alignment

The absolute focus alignment between the telescope focal plane and each instrument shall be ≤ ± 11mm. This is shared between the different interfaces as follows:

- **Internal Instrument Alignment**
  The instruments shall be mounted on the OB with an accuracy of ≤ ± 3mm in axial direction. The instrument internal alignment is in the responsibility of the instrument manufacturers.

- **Instrument w.r.t. Telescope**
  The Optical Bench shall be mounted w.r.t. the CVV with an accuracy of ≤ ± 5mm.

- **Internal Telescope Alignment**
  The telescope internal alignment accuracy shall be ≤ ± 9mm. This value includes ± 5mm variation during one orbit above 40000km altitude. The telescope internal alignment is in the responsibility of the telescope manufacturer

3.2 Lateral Focus and Tilt Alignment

The overall tilt error shall be smaller than 12 arcmin (cone angle). This error corresponds to a lateral misalignment of 16mm. The overall tilt error has to be shared by several contributions and split between lateral and tilt requirements.

The following table shows “reasonable numbers” for the individual contributions and shows the requirements for lateral and tilt alignment (based on ISO experience):

Alignment Step	Axis (arcmin)	Lateral (mm)	ResultingTilt (arcmin)
Instrument internal	8	3	9.11
OB w.r.t. CVV	1	0.5	1.2
Telescope knowledge	NA	1	1.5
PLM / Telescope adjustment	1	1	1.8
Telescope stability	NA	0.1	0.1
Instrument stability 1)			
PLM stability (ISO type)	0.4	0.3	0.6
Total			9.5

Table 3.2-1: Summary of Lateral and Tilt Alignment Requirements

1) Included in instrument adjustment

A distance of 2288mm between secondary mirror and focal plane has been assumed for the table above. The new value which has been used for this document is 2638mm.

We understand Table 3.2-1 as reasonable breakdown of the overall requirement of 12 arcmin between lateral and tilt values. The system level requirements are fulfilled as long as the 12 arcmin value has been achieved, even if some figures are greater than in Table 3.2-1.

3.3 Roll Requirement

The roll error shall be less than 1 degree. This requirement is not shared between the different interfaces.

3.4 LOU to HIFI Alignment Requirements

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

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.

The LOU rotations Rx, Ry, Rz are about the cryostat window.

The alignment requirements for the LOU w.r.t. the HIFI FPU must also be satisfied for ground tests of e.g. the coupling of the LOU to the mixers inside the FPU (TBC by HIFI).

Stability Requirements for LOU w.r.t. HIFI

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

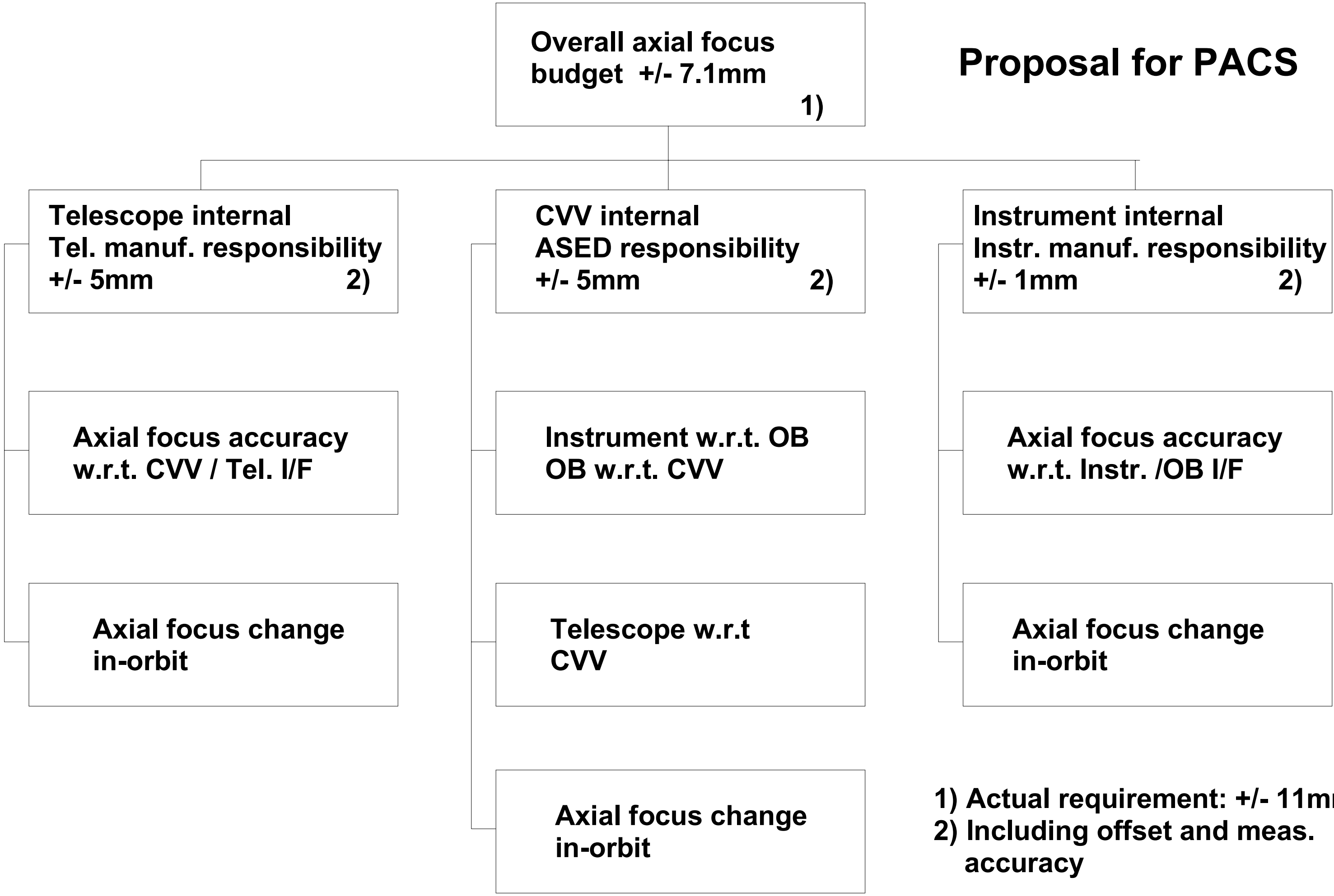
The very high stability along the y axis should be regarded as a goal, which may be verified by analysis.

3.5 Preliminary Alignment Budget Definition

A revision of the IID-A requirements is currently under discussion. During the HOWG meeting, 11.03.02, a new alignment budget has been presented by Astrium on request of ESA. The budget, currently under discussion, is shown in the next Figures. Besides the overall budget the responsibility share between Telescope, Instrument and CVV is shown. The budget is valid for in-orbit conditions.

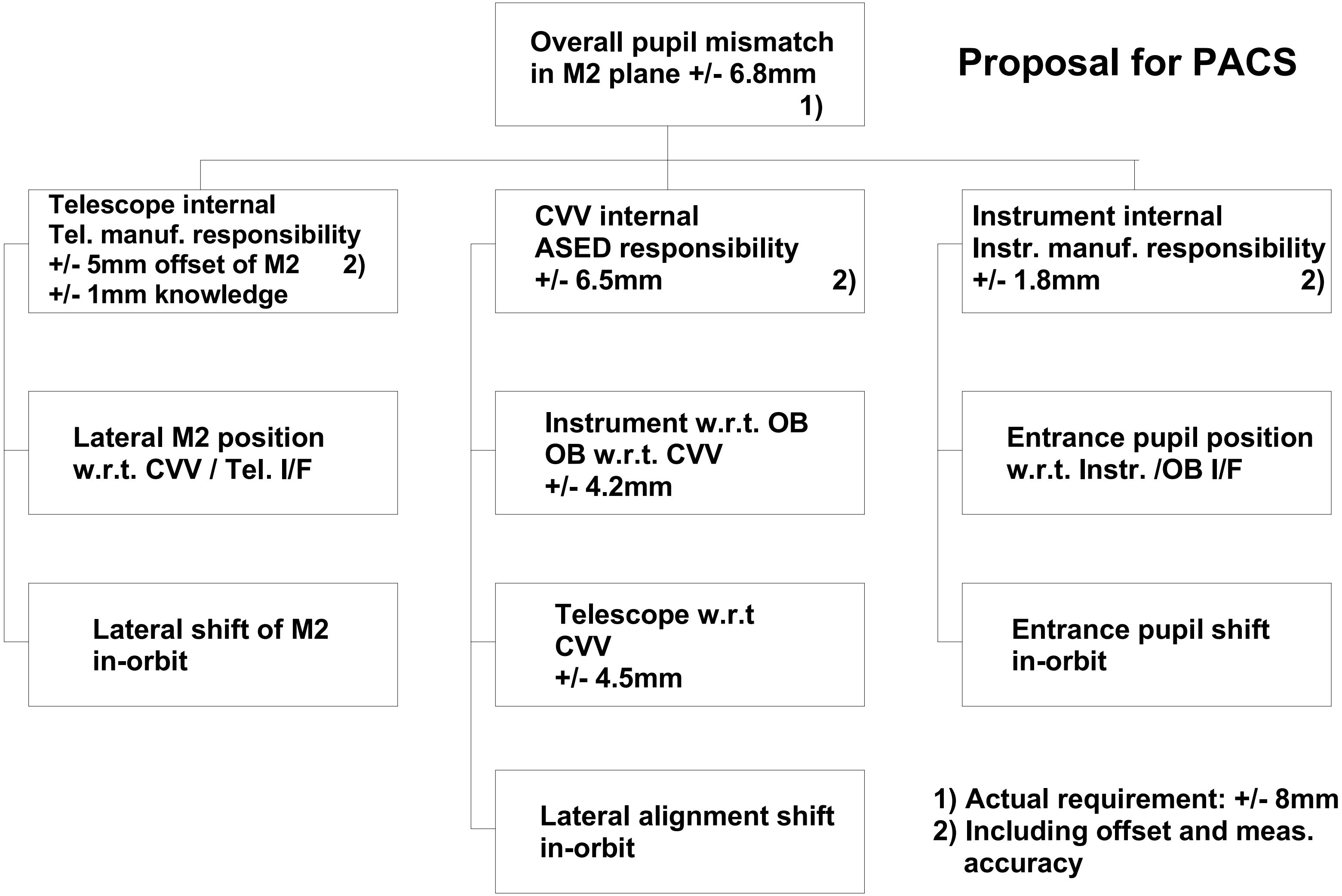
The values shown have been calculated for a confidence level of 1σ and rss summation. During the a.m. meeting it has been agreed that the alignment budget shall be based on a confidence level of 2σ. Therefore, the presented tables must be updated to take into account now the 2σ uncertainties and summation rules. Therefore, they can serve only as guideline for the planned update. The values presented are achievable values. For a new requirement definition system margin must be foreseen. In this context the figures shown on the following pages are not frozen they shall serve as basis for further discussion.

Proposal for PACS



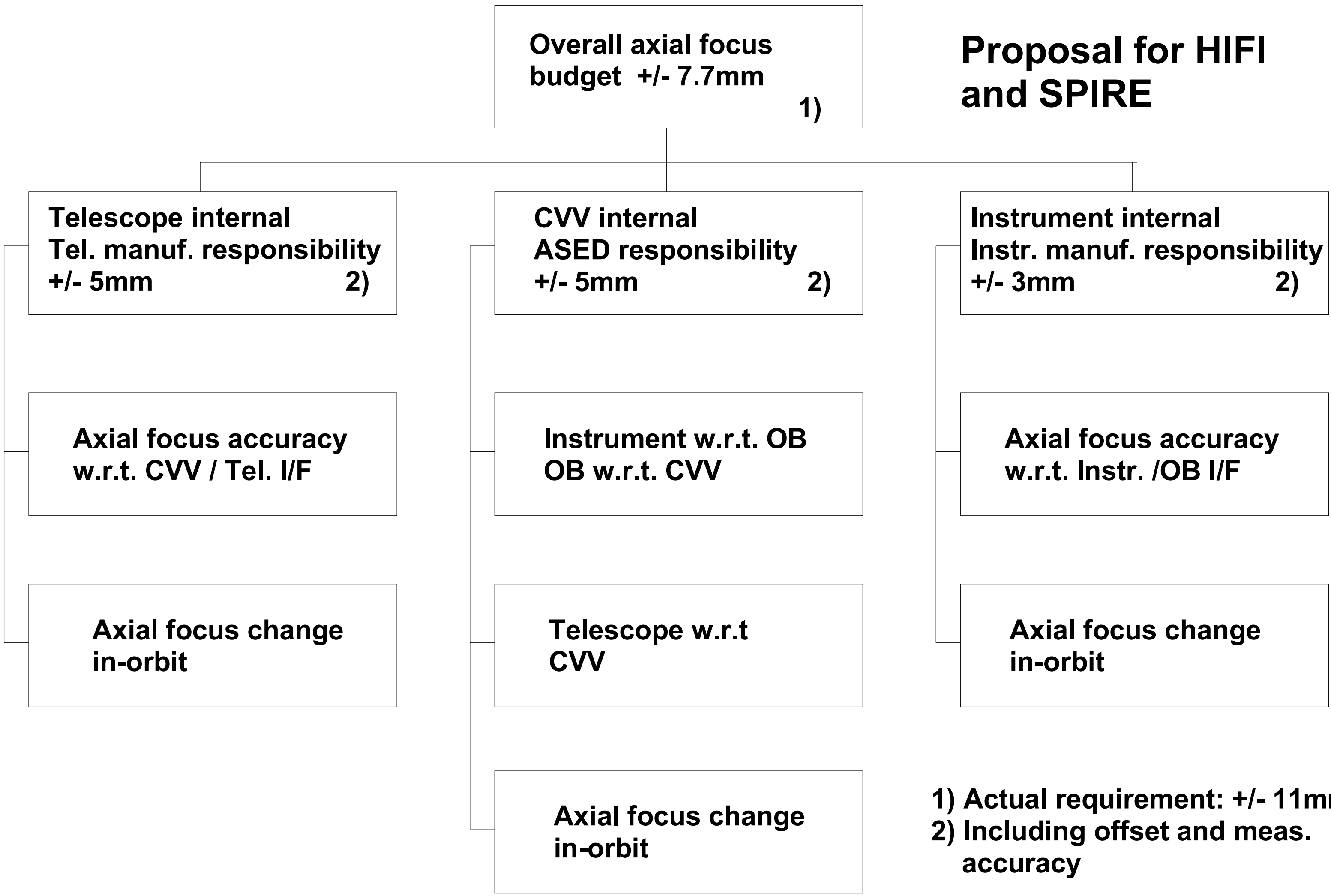
1) Actual requirement: +/- 11mm
2) Including offset and meas. accuracy

Proposal for PACS



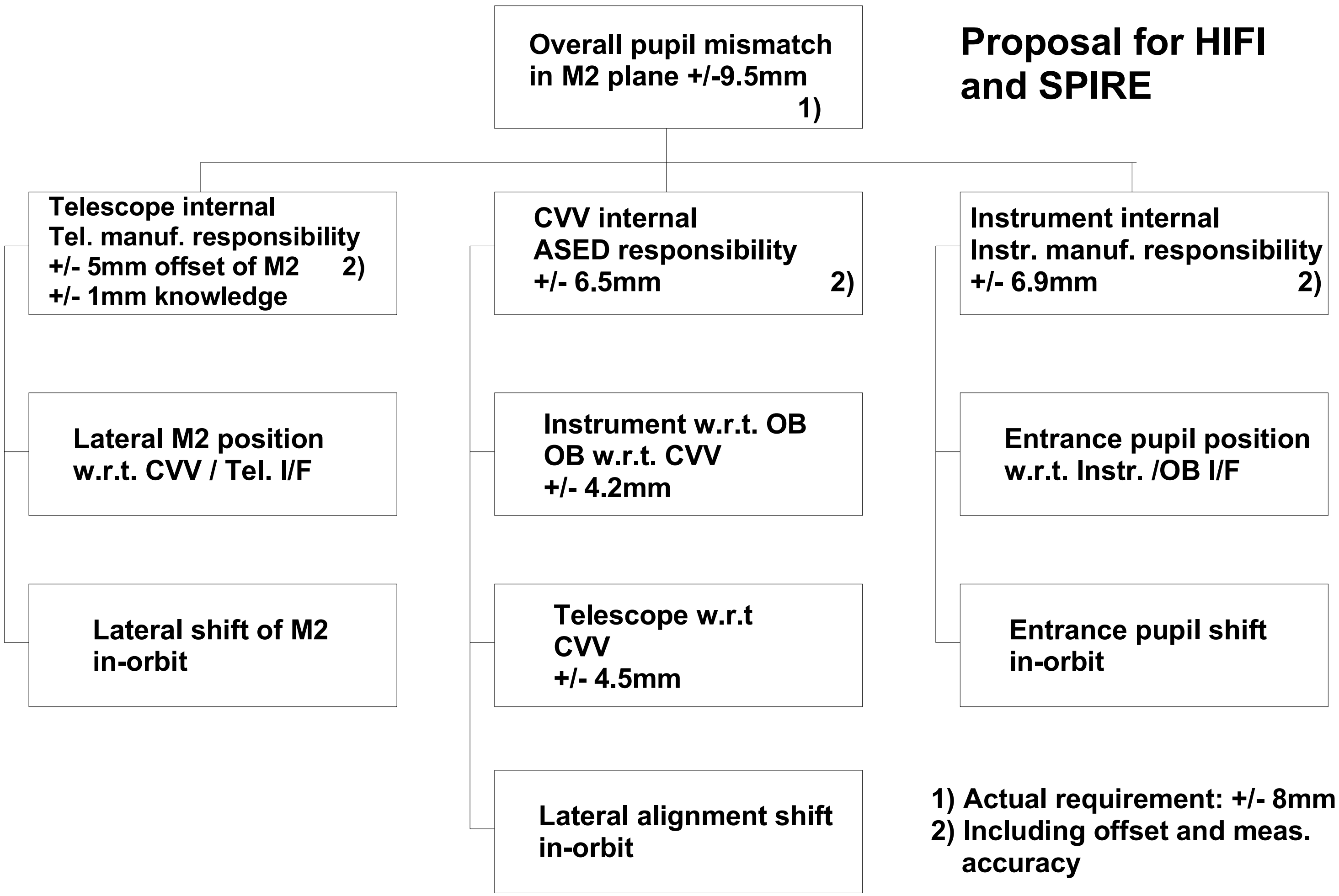
1) Actual requirement: +/- 8mm
2) Including offset and meas. accuracy

Proposal for HIFI and SPIRE



1) Actual requirement: +/- 11mm
2) Including offset and meas. accuracy

Proposal for HIFI and SPIRE



1) Actual requirement: +/- 8mm
2) Including offset and meas. accuracy

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 LOU 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.

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 TBC (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 cover, evacuation and cool down.

8. Re-adjustment of the tank straps and alignment control using the LOU alignment camera.

9. LOU integration and alignment measurement w.r.t. the HIFI FPU via two additional alignment windows using theodolite and LOU alignment camera If necessary adjustment of LOU w.r.t. HIFI using the LOU mounting struts..

10. Telescope integration.

11. Alignment measurement of the telescope reference cube w.r.t. the CVV cube as shown in Figure 4-5. If necessary adjustment.

12. After mating of the SVM with the PLM the SVM master alignment cube will be measured w.r.t. the CVV cube.

13. Alignment check after evacuation and cool down.

14. 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 will shall be delivered with dowel pins. This is actually the case for PACS and HIFI. For SPIRE this is an open point to be discussed. 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.

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) TBC.

The measurement principle is explained in the following figures. Please note, that the alignment cube positions are only shown as an example to explain the alignment method. The real position is defined in chapter7.

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 in all directions TBC
   - SPIRE: TBC

2. Optical Bench adjustment range in each direction 1.5mm via the 16 tank straps

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.

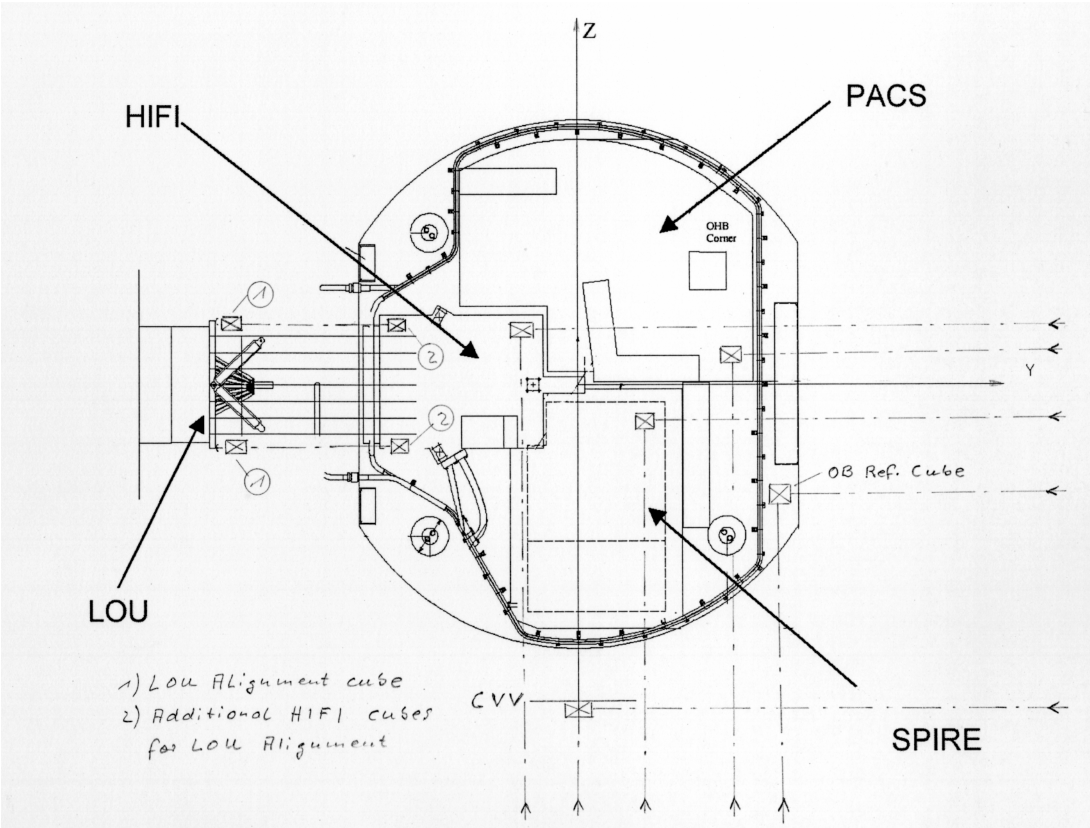


Figure 4-1: Alignment References

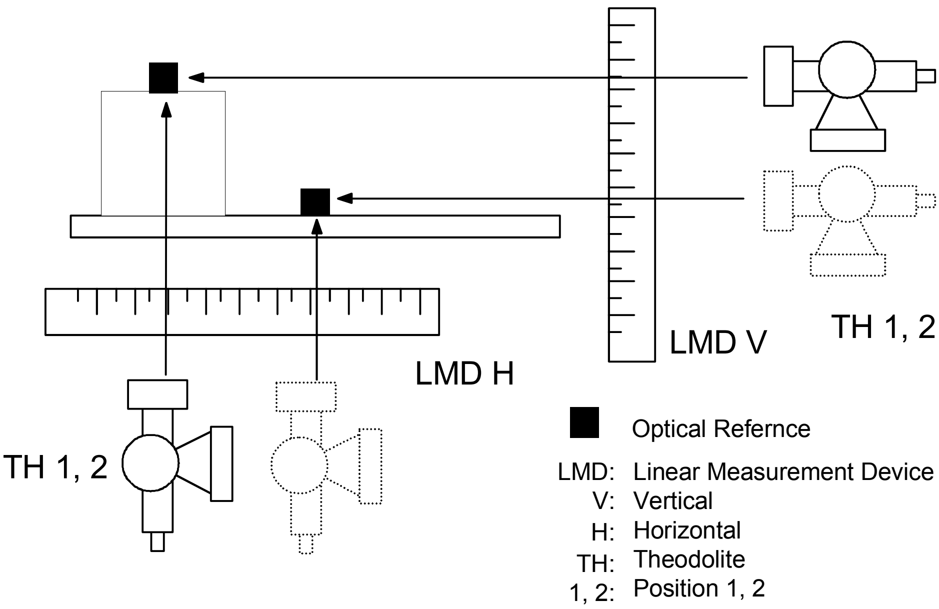


Figure 4-2: Instrument Alignment w.r.t. Optical Bench

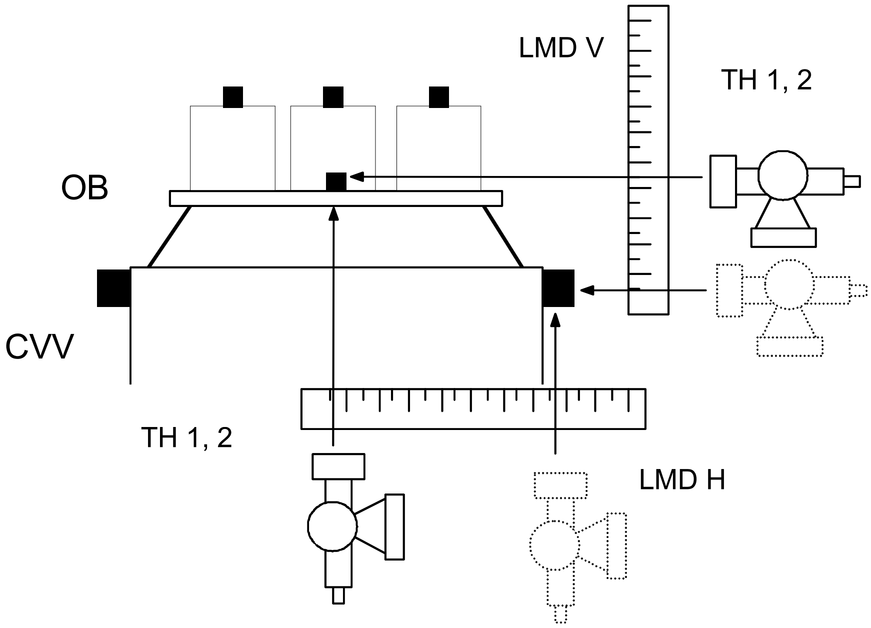


Figure 4-3: Optical Bench Alignment w.r.t. CVV

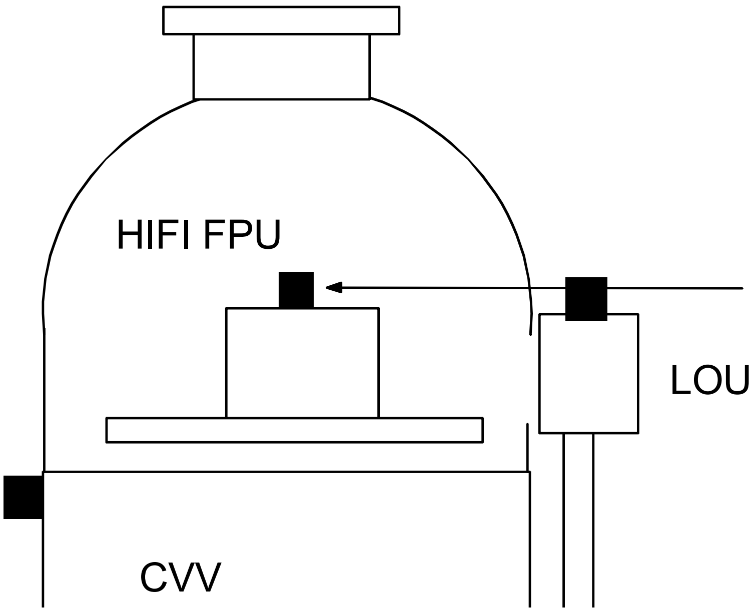


Figure 4-4: LOU Alignment w.r.t. HIFI
(With the LOU Camera proposed by, HIFI TBC by HIFI)

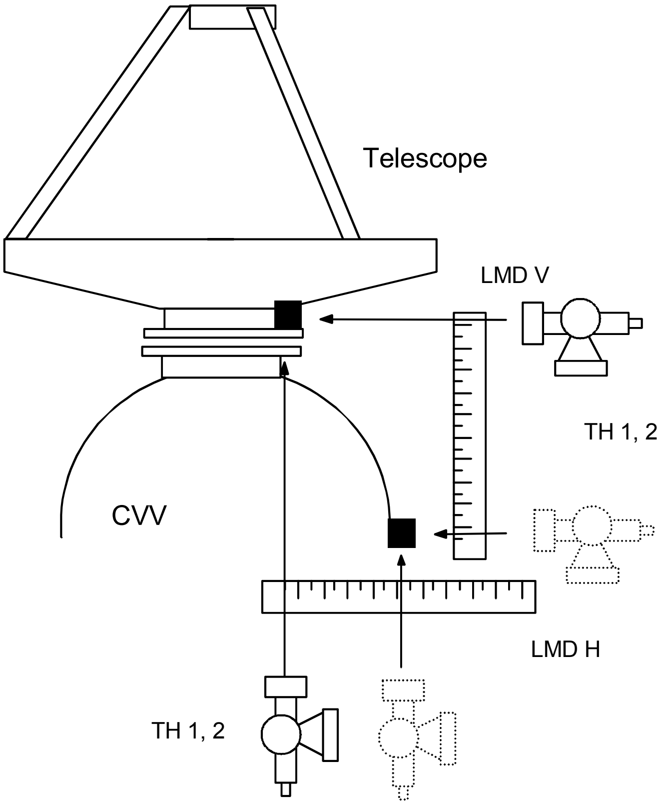


Figure 4-5: Telescope Alignment w.r.t. CVV Reference Cube

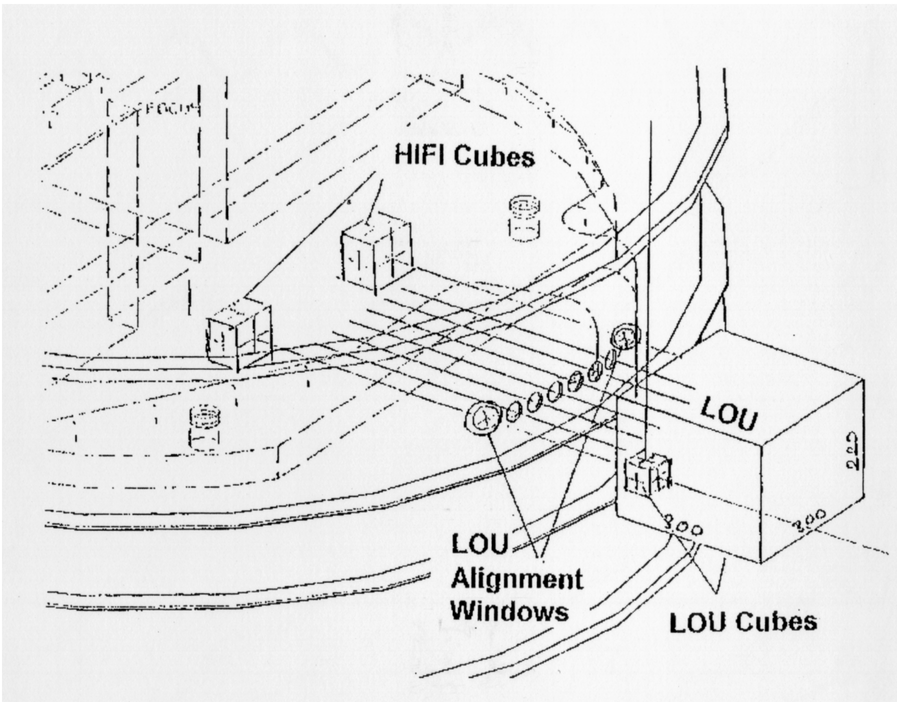


Figure 4-6: Detection of HIFI using the LOU Alignment Windows

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

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 S/C 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.
In chapter 7 we will define for all measurements the direction from which the alignment measurements will be performed during system level alignment. The internal instrument alignment shall be performed from the same directions in order to minimise the error.

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.

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.

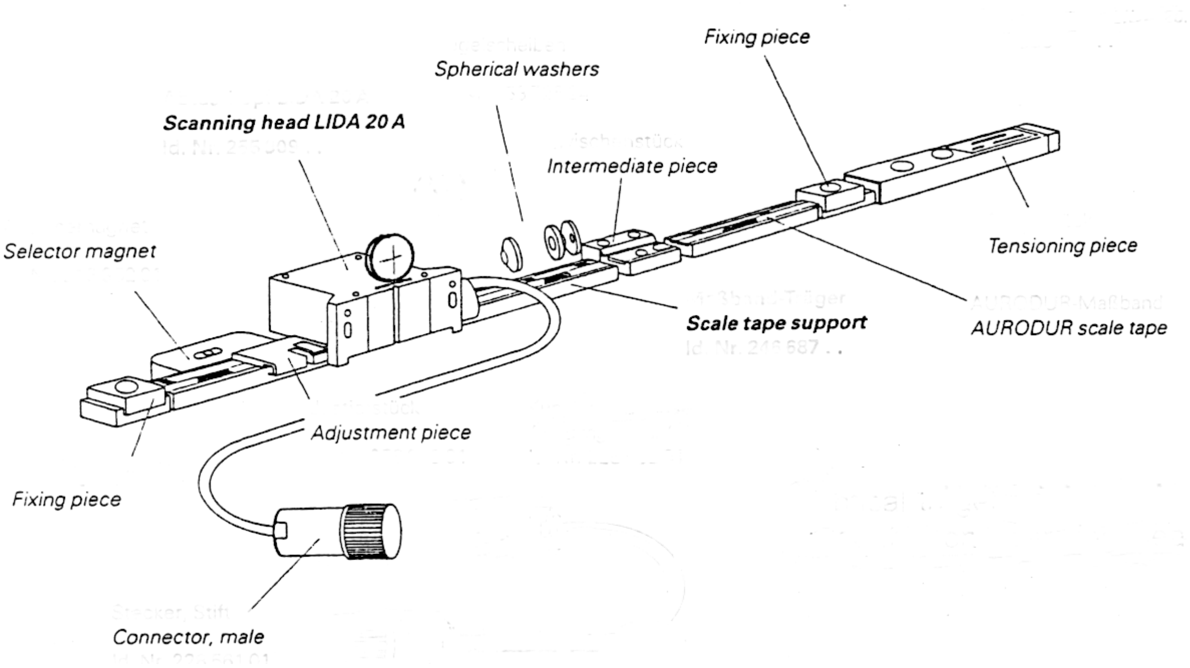


Figure 4-7: Linear Measurement Device

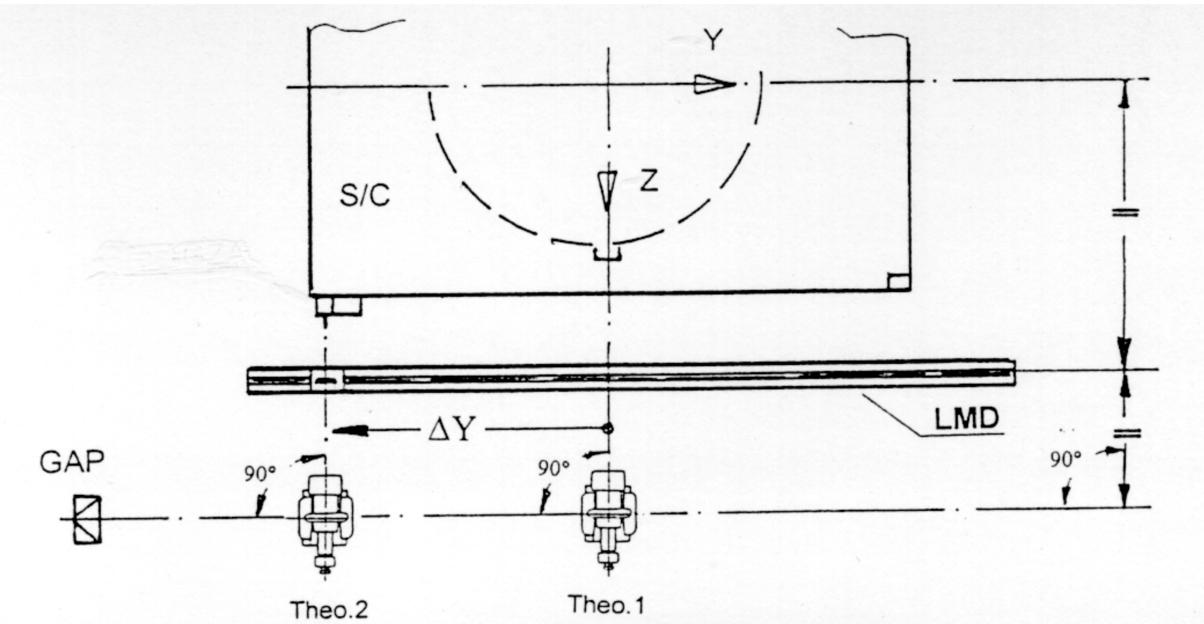


Figure 4-8: Lateral Distance Measurement using a LMD

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 temperature

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

For the initial alignment performed with the EQM 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 LOU 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. 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 LOU alignment camera. The test sequence for the EQM (concerning alignment) is as follows:

.....PLM Integration→Alignment (1)→Closing Cryostat→Evacuation→Alignment

check →Cooling→Alignment check→Other Tests.....

1) See chapter 4 for the individual alignment steps

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

The main tasks are the following:

- Early verification of the alignment as far as possible (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.

Monitoring the shift and angular deviation of the OB after cryostat evacuation and cool down will be performed using the LOU alignment cameras TBC.

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). A distance measurement in y direction is also possible, however, with reduced accuracy TBC. This is no problem for the LOU alignment because the distance requirement w.r.t. this axis is very comfortable (± 15mm for LOU w.r.t. HIFI FPU).

With the actual feature having also a measurement capability in y direction (with improved measurement accuracy) with the LOU alignment camera this camera will also be used to re-adjust the tank support suspension devices after cool down under alignment control.

The advantage to have the LOU alignment camera would be, that it can also be used for the STM programme inside the TV chamber and no additional alignment window is needed.
With the actual feature having also a measurement capability in y direction (with improved measurement accuracy) with the LOU alignment camera this camera will also be used to re-adjust the tank support suspension devices after cool down under alignment control.

The LOU alignment camera will be used at the following stages during the whole AIV programme:

1. Alignment of LOU w.r.t. HIFI FPU verification.

2. Re-adjustment of Tank Suspension after cool down.

3. Measurement of CVV shrinkage w.r.t. OB (HIFI) inside TV chamber with the STM and confirmation of the mathematical model.

4. Partial measurement of LOU w.r.t. HIFI stability and confirmation of mathematical model TBC.

5. Alignment check before and after environmental testing and after evacuation and cool down.

Measurement no. 3 and 4 will be performed at nearly in-orbit representative CVV temperatures.

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.

The main tasks are as follows:

- Qualification of the structure (stability)
  (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 LOU alignment camera)

- Confirmation of the mathematical model

The actual test sequence is as follows (only alignment related steps, this sequence might be changed in the relevant AIV documents):

.....PLM Integration→Alignment→Closing Cryostat→Evacuation→Alignment check→Warm vibration→Alignment check → Cooling→Alignment check→Telescope integration→ Telescope alignment→.....→TB / TV Test→Alignment check→ .....→Cold vibration→Alignment check→.....→Acoustic noise→Alignment check......

Monitoring of the alignment stability at nearly in-orbit representative CVV temperature will be performed during the TB/TV test using the LOU alignment camera TBC.

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.

The test sequence is as follows (only alignment relevant steps):

.....PLM integration→Alignment→Evacuation→Alignment check→Cooling →Alignment check→.....→Telescope integration→Telescope alignment →Transport to test facility→.....→Alignment check→Cold vibration→Alignment check→.....→TB/TV test→Alignment check→.....→Acoustic noise→Alignment check

After mating of the SVM with the PFM the SVM master alignment cube will be measured w.r.t. the CVV cube. The alignment of the AOCS related components w.r.t. the SVM master alignment cube is the task of Alenia.

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)

- Thermoelastic distortion
  Covers the drift errors in-orbit as calculated with the load cases LC1 through LC4 (see next page).

For the PDR 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 4 load cases as defined by Alcatel LC1 through LC4).

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

- LC 1 WS 0°/0° EOL (Pitch/Roll)
- LC 2 WS +30°/0° EOL
- LC 3 WS –30°/0° EOL
- LC 4 SS 0°/0° BOL
- LC 5 Cryostat cool down, OB at 30K and CVV at 293K
- LC 6 Cryostat in TB/TV chamber, OB at 13K and CVV at 88K

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

- LC 7 Pressure release
- LC 8 Gravity release

The difference for the BOL and EOL calculation is the following:
EOL has been calculated for the “hot case” (Solar constant at maximum and absorption coefficient for the optical sun reflector max. value).
BOL has been calculated for the “cold case” (Solar constant at minimum and absorption coefficient for the optical sun reflector min. value).

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 at this time and therefore the HEPLM FEM does not show instrument internal thermal distortion effects. Therefore only one common point on the OB is reflected in the FEM analysis for the three instruments. An update of this analysis is planned for phase C/D.

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 (IID-A for instrument w.r.t. telescope and IID-B for LOU alignment). A further comparison is made w.r.t. the potentially new requirements currently under discussion in the HOWG but not yet agreed.

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). In each error class rss summation has been applied. For the in-orbit changes (thermoelastis distortion) the difference of LC4 and LC1 and additionally LC3 and LC1 has been calculated. The max. value has been used for calculation. 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, however, this is not explicitly required in IID-A.

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 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.

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.

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	3)	Instrument manufacturer responsibility TBC by PACS
3	Telescope internal alignment w.r.t. telescope reference cube / mounting I/F	t u b 2)	1) 4.3	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	b	0.05		
19	due to TB/TV testing	b	0.05	12.4	
20	**Remaining adjustment offset**	b	0.4	20	
21	**In-orbit effects**				
22	Gravity release	b	0.092	1.1	
23	Pressure release	b	0.12	0.85	

24	Thermoelastic distortion				
25	LC4-LC1	t	0.016	0.014	Includes also difference between BOL and EOL
26	LC3-LC1	t	0.010	0.017	
27	**Total Error CVV**				
28	Uncertainty (rss)	u	0.96	54.6	
29	Bias (rss)	b	0.45	50.6	
30	Total including thermoelastic distortion (linear summation)		**1.4**	**105.2**	No. 28 plus No. 29 Plus No. 25
31	**Requirement CVV**				
32	IID-A		**5.0**	4)	
33	HOWG proposed update (currently under discussion)		**5.0**		
34	**Total Error PLM**				
35	Uncertainty (rss)	u	1.4	54.6	
36	Bias (rss)	b	4.3	50.6	
37	Total incl. thermoelastics		**5.8**	105.2	Instrument w.r.t. Tel. focus
38	**Requirement PLM**				
39	IID-A		**11.0**	**3600**	
40	HOWG proposed update (currently under discussion)		**7.1**		Valid for a confidence level of 1σ

1) The thermal stability is included in the bias value
2) In-orbit effects included
3) No data available at this time, but not critical because the requirement is 1°
4) No break down in IID-A

The 11mm requirement from IID-A can be met, even with comfortable margin. The 7.1mm proposed in the HOWG meeting (see chapter 3.5) must be updated to a confidence level of 2σ before comparison with the 5.8mm. 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 b 2)	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	0.30		5% of absolute value
14	CVV	u	0.30		
15	**Setting effects**				
16	due to launch (vibration)				
17	due to TB/TV testing	b	0.05	12.4	
18	**Remaining adjustment offset**	b	0.3	20	
19					

20	**In-orbit effects**				
21	Gravity release	b	0.10	5.2	
22	Pressure release	b	0.032	0.78	
23	Thermoelastic distortion				
24	LC4-LC1	t	0.012		Contribution from Ry, Rz incl. Includes also difference between BOL and EOL
25	LC3-LC1	t	0.019		Contribution from Ry, Rz incl
26	**Total Error CVV**				
27	Uncertainty (rss)		0.92	47.1	
28	Uncertainty (rss) due to Ry, Rz		0.60		47.1arcsec ↔ 0.60mm
29	Uncertainty (rss) total		1.1		Contribution from Ry, Rz incl.
30	Bias (rss)		0.34	53.8	
31	Bias (rss) due to Ry, Rz		0.69		53.8arcsec ↔ 0.69mm
32	Bias (rss) total		0.77		Contribution from Ry, Rz incl.
33	Total including thermoelastic distortion (linear summation)		**1.9**		No. 29 plus No. 32 plus No. 25
34	Pupil Mismatch in M2 Plane		**2.7**		1.9 * SQRT(2) (half cone)
35	**Requirement CVV**				
36	IID-A				
37	Bias		**1.7**		Bias incl. Stability
38	Uncertainty		**4.9**		
39	HOWG proposed update (currently under discussion)		**6.5**		Uncertainty + Bias + Stability
40	**Total Error PLM**				
41	Uncertainty (rss)		1.2		
42	Bias (rss)		1.5		
43	Total including thermoelastic distortion (linear summation)		2.8		
44	Pupil mismatch in M2 plane		**4.0**		2.8 * SQRT(2) (half cone)
45	**Requirement PLM**				
46	IID-A		**8.0**		
47	HOWG proposed update (currently under discussion)		**6.8**		

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

The 8mm requirement from IID-A for the pupil mismatch can be met, even with comfortable margin. The 6.8mm as proposed in the HOWG meeting can also be met with sufficient 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	3)	Instrument manufacturer responsibility TBC by SPIRE
3	Telescope internal alignment w.r.t. telescope reference cube / mounting I/F	t u b 2)	1) 4.3	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	b	0.05		
19	due to TB/TV testing	b	0.05	12.4	
20	**Remaining adjustment offset**	b	0.4	20	
21	**In-orbit effects**				
22	Gravity release	b	0.092	1.1	
23	Pressure release	b	0.12	0.85	

24	Thermoelastic distortion				
25	LC4-LC1	t	0.016	0.014	Includes also difference between BOL and EOL
26	LC3-LC1	t	0.010	0.017	
27	**Total Error CVV**				
28	Uncertainty (rss)	u	0.96	54.6	
29	Bias (rss)	b	0.45	50.6	
30	Total including thermoelastic distortion (linear summation)		**1.4**	**105.2**	No. 28 plus No. 29 Plus No. 25
31	**Requirement CVV**				
32	IID-A		**5.0**	4)	
33	HOWG proposed update (currently under discussion)		**5.0**		
34	**Total Error PLM**				
35	Uncertainty (rss)	u	1.1	54.6	
36	Bias (rss)	b	4.3	50.6	
37	Total incl. thermoelastics		**5.5**	105.2	Instrument w.r.t. Tel. focus
38	**Requirement PLM**				
39	IID-A		**11.0**	**3600**	
40	HOWG proposed update (currently under discussion)		**7.7**		Valid for a confidence level of 1σ

1) The thermal stability is included in the bias value
2) In-orbit effects included
3) No data available at this time, but not critical because the requirement is 1°
4) No break down in IID-A

The 11mm requirement from IID-A can be met, even with comfortable margin. Also the 7.7mm as proposed in the HOWG meeting can be met. The 7.7mm proposed in the HOWG meeting (see chapter 3.5) must be updated to a confidence level of 2σ before comparison with the 5.5mm. 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 b 2)	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	0.30		5% of absolute value
14	CVV	u	0.30		
15	**Setting effects**				
16	due to launch (vibration)				
17	due to TB/TV testing	b	0.05	12.4	
18	**Remaining adjustment offset**	b	0.3	20	
19					

20	**In-orbit effects**				
21	Gravity release	b	0.10	5.2	
22	Pressure release	b	0.032	0.78	
23	Thermoelastic distortion				
24	LC4-LC1	t	0.012		Contribution from Ry, Rz incl. Includes also difference between BOL and EOL
25	LC3-LC1	t	0.019		Contribution from Ry, Rz incl
26	**Total Error CVV**				
27	Uncertainty (rss)		0.92	47.1	
28	Uncertainty (rss) due to Ry, Rz		0.60		47.1arcsec ↔ 0.60mm
29	Uncertainty (rss) total		1.1		Contribution from Ry, Rz incl.
30	Bias (rss)		0.34	53.8	
31	Bias (rss) due to Ry, Rz		0.69		53.8arcsec ↔ 0.69mm
32	Bias (rss) total		0.77		Contribution from Ry, Rz incl.
33	Total including thermoelastic distortion (linear summation)		**1.9**		No. 29 plus No. 32 plus No. 25
34	Pupil Mismatch in M2 Plane		**2.7**		1.9 * SQRT(2) (half cone)
35	**Requirement CVV**				
36	IID-A				
37	Bias		**1.7**		Bias incl. Stability
38	Uncertainty		**4.9**		
39	HOWG proposed update (currently under discussion)		**6.5**		Uncertainty + Bias + Stability
40	**Total Error PLM**				
41	Uncertainty (rss)		1.7		
42	Bias (rss)		1.4		
43	Total including thermoelastic distortion (linear summation)		**3.2**		
44	Pupil mismatch in M2 plane		**4.5**		3.2 * SQRT(2) (half cone)
45	**Requirement PLM**				
46	IID-A		**8.0**		
47	HOWG proposed update (currently under discussion)		**9.5**		

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

The 8mm requirement from IID-A for the pupil mismatch can be met even with sufficient margin. This improvement could be realised du 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	3)	Instrument manufacturer responsibility TBC by HIFI
3	Telescope internal alignment w.r.t. telescope reference cube / mounting I/F	t u b 2)	1) 4.3	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		0.05		
19	due to TB/TV testing	b	0.05	12.4	
20	**Remaining adjustment offset**	b	0.4	20	
21	**In-orbit effects**				
22	Gravity release	b	0.092	1.1	
23	Pressure release	b	0.12	0.85	

24	Thermoelastic distortion				
25	LC4-LC1	t	0.016	0.014	Includes also difference between BOL and EOL
26	LC3-LC1	t	0.010	0.017	
27	**Total Error CVV**				
28	Uncertainty (rss)	u	0.96	54.6	
29	Bias (rss)	b	0.45	50.6	
30	Total including thermoelastic distortion (linear summation)		**1.4**	**105.2**	No. 28 plus No. 29 Plus No. 25
31	**Requirement CVV**				
32	IID-A		**5.0**	4)	
33	HOWG proposed update (currently under discussion)		**5.0**		
34	**Total Error PLM**				
35	Uncertainty (rss)	u	2.9	54.6	
36	Bias (rss)	b	4.8	50.6	
37	Total incl. thermoelastics		**7.8**	105.2	Instrument w.r.t. Tel. focus
38	**Requirement PLM**				
39	IID-A		**11.0**	**3600**	
40	HOWG proposed update (currently under discussion)		**7.7**		Valid for a confidence level of 1σ
41	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
3) No data available at this time, but not critical because the requirement is 1°
4) No break down in IID-A

The 11mm requirement from IID-A can be met with sufficient margin. The 7.7mm proposed in the HOWG meeting (see chapter 3.5) must be updated to a confidence level of 2σ before comparison with the 7.8mm. The biggest contribution is coming from the telescope bias (4.3mm) and the internal alignment of HIFI itself (4.8 instead of the 3mm discussed at the HOWG meeting, 11.03.02).

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 b 2)	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	0.30		5% of absolute value
14	CVV	u	0.30		
15	**Setting effects**				
16	due to launch (vibration)				
17	due to TB/TV testing	b	0.05	12.4	
18	**Remaining adjustment offset**	b	0.3	20	
19					

20	**In-orbit effects**				
21	Gravity release	b	0.10	5.2	
22	Pressure release	b	0.032	0.78	
23	Thermoelastic distortion				
24	LC4-LC1	t	0.012		Contribution from Ry, Rz incl. Includes also difference between BOL and EOL
25	LC3-LC1	t	0.019		Contribution from Ry, Rz incl
26	**Total Error CVV**				
27	Uncertainty (rss)		0.92	47.1	
28	Uncertainty (rss) due to Ry, Rz		0.60		47.1arcsec ↔ 0.60mm
29	Uncertainty (rss) total		1.10		Contribution from Ry, Rz incl.
30	Bias (rss)		0.34	53.8	
31	Bias (rss) due to Ry, Rz		0.69		53.8arcsec ↔ 0.69mm
32	Bias (rss) total		0.77		Contribution from Ry, Rz incl.
33	Total Error including thermoelastic distortion (linear summation)		**1.9**		No. 28 plus No. 31 plus No. 24
34	Pupil Mismatch in M2 Plane		**2.7**		1.9 * SQRT(2) (half cone)
35	**Requirement CVV**				
36	IID-A				
37	Bias		**1.7**		Bias incl. Stability
38	Uncertainty		**4.9**		
39	HOWG proposed update (currently under discussion)		**6.5**		Uncertainty + Bias + Stability
40	**Total Error PLM**				
41	Uncertainty		10.1		
42	Bias		1.7		
43	Total including thermoelasic		11.9		
44	**Pupil mismatch in M2 plane**		**16.8**		11.9 * SQRT(2) (half cone)
45	**Requirement**				
46	IID-A		**8.0**		
47	HOWG proposed update (currently under discussion)		**9.5**		
48	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

The overall error for the HIFI pupil mismatch is 16.8mm. The 8mm requirement from IID-A for the pupil mismatch can not be fulfilled due to the big internal HIFI contribution of 11mm (in each direction). The HIFI proposed requirement of 24mm (half cone) can be met with sufficient margin left.

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	20	20	Accuracy of LOU Alignment Camera TBC
5	Measurement error on HIFI alignment device	u							n.a. in case LOU alignment camera is available
6	Measurement error on LOU alignment device	u							n.a. in case LOU 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	b	0.05	0.05	0.05	12	12	12	
17	**In-orbit effects**								
18	Gravity release	b	0.032	0.007	0.004	1.9	0.53	27.1	
19	Pressure release	b	0.17	0.086	0.003	2.5	0.059	49.6	
20	Thermoelastic distortion								
21	LC4-LC1	b	0.014	0.013	0.001	0.66	0.22	0.54	Includes also difference between BOL and EOL
22	LC3-LC1	b	0.008	0.008	0.001	0.17	0.12	0.57	
23	**Total Error (Bias and Uncertainty)**								
24	Uncertainty (rss)		0.50	0.67	0.50	42.2	31.9	31.9	
25	Uncertainty (rss) due to Ry		0.046						
26	**Uncertainty (rss) total**		**0.50**	**0.67**	**0.50**	**42.2**	**31.9**	**31.9**	
27	Bias (rss)		0.19	0.14	0.11	46.5	31.5	69.9	
28	Bias (rss) due to Ry		0.046						
29	**Bias (rss) total**		**0.20**	**0.14**	**0.11**	**46.5**	**31.5**	**69.9**	
30	**Total including thermoelastic distortion** (linear summation)		**0.71**	**0.82**	**0.61**	**89.4**	**63.6**	**101.9**	No. 26 plus No. 29 plus 21 (22)
31	**Requirement**								
32	Alignment		0.75	15	0.75	136.8	1)	136.8	1) included in x
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.

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 0.71mm 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 LC3-LC1 which takes into account a change of the pitch from 0° to –30° at EOL conditions (steady state analysis) for an unlimited time interval. In y direction a stability of 0.008mm for LC3-LC1 can be achieved. It is expected that due to the high heat capacity of the HSS and the heat capacity of the LOU the goal value of 0.003mm within 100sec. can be achieved. For the other stability requirements we see no problem.

6.2 LOS Stability

In the H-EPLM Specification update it is foreseen to implement a stability requirement for the instruments LOS w.r.t. the SVM / PLM interface.

During observation phase, the alignment stability of the instruments LOS w.r.t. the SVM / PLM interface plane shall be better than:

- ± 0.2 arcsec (± 0.05 arcsec goal)
- ± 0.1 arcsec in 1 minute (± 0.02 arcsec goal)

Around each axis taking into account worst case Sun Aspect Angle variation, season effects and temperature gradient at SVM / PLM interface. The PLM / SVM is assumed to be perfect.

In this chapter a preliminary assessment will be provided. A distortion analysis has been performed based on the temperature maps for the different load cases as defined by Alcatel. A more detailed description of the FEM is given in [RD 2].

For the stability assessment the difference of the 4 load cases has been calculated. The results are as follows:

Definition of the load cases:

- LC 1 WS 0°/0° EOL (Pitch/Roll)
- LC 2 WS +30°/0° EOL
- LC 3 WS –30°/0° EOL
- LC 4 SS 0°/0° BOL

Results:

- LC1 – LC2 = 0.055 arcsec
- LC1 – LC3 = 0.81 arcsec
- LC1 – LC4 = 0.63 arcsec
- LC2 – LC3 = 0.86 arcsec
- LC2 – LC4 = 0.69 arcsec
- LC3 – LC4 = 0.18 arcsec

The preliminary data show that the requirement of 0.2 arcsec cannot be met for all cases (assuming unlimited time intervals).

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.

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. Only the PACS cube is visible from two sides during system level alignment. For HIFI and SPIRE new positions have been defined by Astrium, shown in Figure 7-1 and specified in the following sections for each instrument. It shall be checked by the instruments if the proposed positions for the alignment cubes are possible.

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.

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.

Pupil Mismatch (in M2 plane**)**

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

HIFI states that the overall pupil mismatch ca be 24.0mm half cone.

The position of the reference cube is shown in Figure 7-1.
The position of the alignment cube centre w.r.t. the OB coordinate system shall be:
x = 409.5mm y = -116.5mm z = 135.0mm

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 4-6).
The LOU must be delivered also with two alignment devices mounted at the + and –z side of the LOU. The exact position must be defined together with HIFI.

For the LOU w.r.t. HIFI alignment the requirements are valid from cube 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 7-1.
The position of the alignment cube centre w.r.t. the OB coordinate system shall be:
x = 448.5mm y = 101.5mm z = 53.5mm

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 7-1.
The position of the alignment cube centre w.r.t. the OB coordinate system shall be:
x = 478.5mm y = 118.0mm z = -53.4mm

7.2 Optical Bench

The three instruments will be measured with respect to OB reference cube.

The position of the OB reference cube will be defined together with the OB manufacturer. The position of the reference cube shall be measured with respect to the OB coordinate system. The accuracy will be defined after the agreement of the alignment requirements.

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 exact position is TBD. 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 shall be mounted at the CVV.

After mating of the SVM and PLM the SVM master cube will be measured w.r.t. the CVV cube.

7.4 Telescope

After the cryostat has been closed the telescope can be integrated. For alignment w.r.t. the CVV cube 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 reference cube is TBD and must be defined in close cooperation with ASEF (visibility on system level).

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 4-6).

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

The alignment windows shall placed in the following positions (warm/cold dimensions) TBC.

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

Exact position and window diameter is TBD.

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

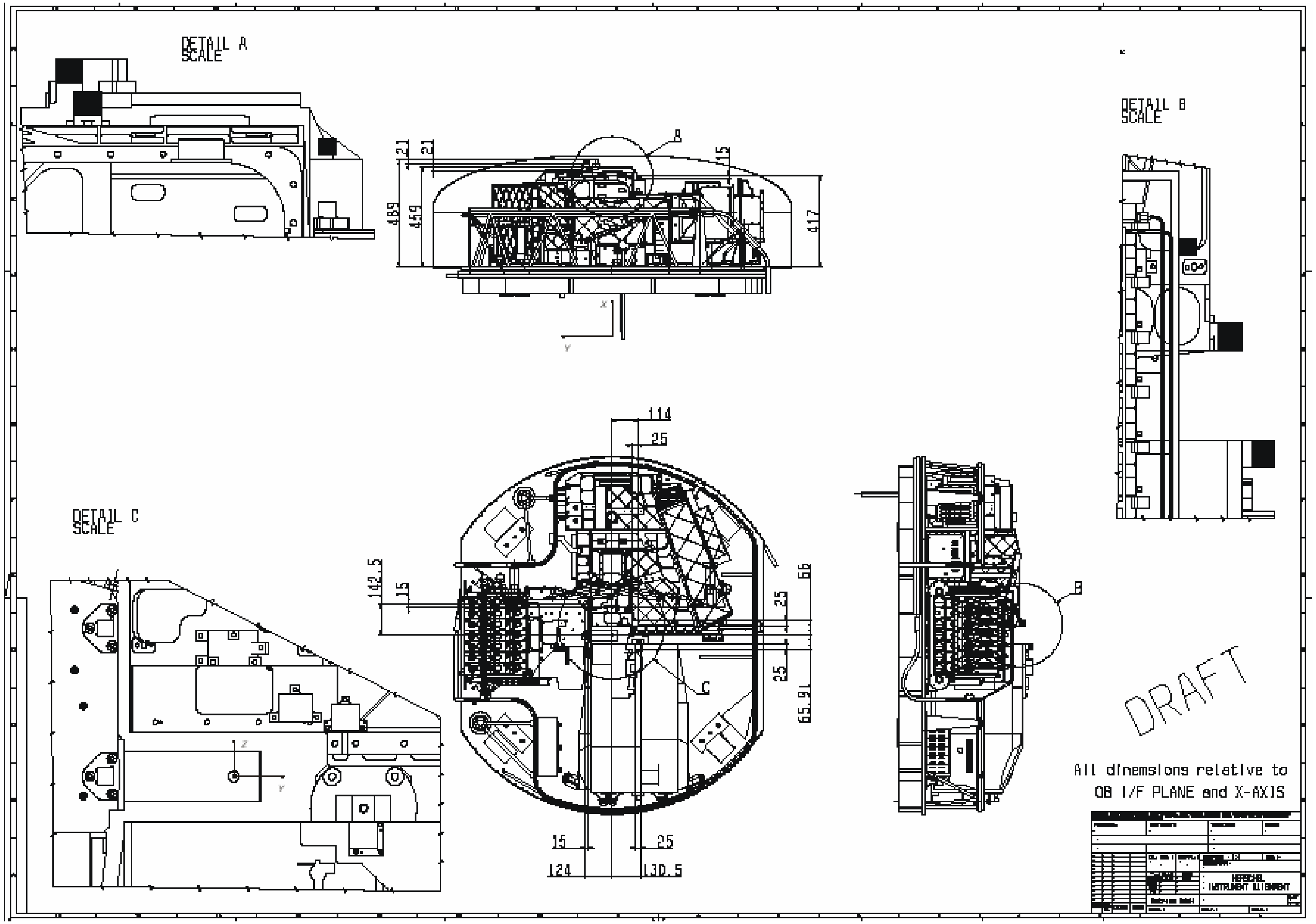


Figure 7-1: Proposed position of instrument alignment references.

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	LOU Alignment Camera	LOU alignment and alignment monitoring		1)
5	Appr.20	Alignment reference cubes	For OB, CVV......		x
6	1	Support Structure for LMD	For vertical and horizontal measurements	2)	
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		3)
9	1	Adapter	For SVM I/F		x
10	1	Adapter	For PLM I/F		x
11	1	Cherry Picker			4)

Table 8-1: Alignment Equipment List (preliminary)

1) The baseline is to use the LOU alignment camera at different stages of system level alignment

2) Made with X95 System TBC

3) It will be checked if the ERS rotary table is available. At this time it will be used by METOP

4) 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 LOU 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 0.71mm 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 5.8mm is achievable. There is no problem compared it to the IID-A requirement of 11mm. The proposed requirement from the HOWG meeting of 7.1mm must be updated to a confidence level of 95%. The biggest contribution is coming from the telescope with a bias of 4.3mm.
The achievable value for SPIRE is 5.5mm. There is comfortable margin against the IID-A. The 7.7mm from the HOWG meeting can also be achieved but will be updated to 95% confidence level.
For HIFI a value of 7.8mm is achievable. There is no problem with the IID-A requirement. Again the 7.7mm from the HOWG meeting must be updated for 95% confidence level. HIFI states (E-mail, dated 24.05.02) 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 (4.0mm achievable) and SPIRE (4.5mm achievable) there is comfortable margin against the IID-A requirement (8mm) and also w.r.t. to the proposed update in the HOWG meeting (6.8mm for PACS and 9.5mm for SPIRE). The achievable pupil mismatch for HIFI is 16.8mm which is appr. two times the value given in IID-A. HIFI itself contributes to this value with 15.5mm. HIFI states that the IID-A value can be relaxed to 24mm half cone (E-mail, dated 7.06.02) which gives sufficient margin on system level.

Based the above considerations new alignment requirements can be defined.
But 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. This must be taken into account for the definition of new requirements.

The following tables summarise the achievable alignment results:

1: Instruments w.r.t. Telescope

	PACS	SPIRE	HIFI	Remarks
Achievable X Direction	±5.8mm	±5.5mm	±7.8mm	
Requirement IID-A HOWG HIFI	 ±11.0mm ±7.1mm	 ±11.0mm ±7.7mm	 ±11.0mm ±7.7mm ±8.5mm	 1) 2)
Achievable Lateral	4.0mm	4.5mm	16.8mm	3)
Requirement IID-A HOWG HIFI	 8.0mm 6.8mm	 8.0mm 9.5mm	 8.0mm 9.5mm 24.0mm	3) 1) 2)

1) Values proposed by Astrium during the HOWG meeting, 11.03.02 (based on 1σ and rss summation). Must be updated to 2σ as stated during the HOWG meeting.
2) Proposed by HIFI
3) Half cone angle

2: LOU w.r.t. HIFI
Alignment

	Δx	Δy	Δz	Rx	Ry	Rz
Achievable value	0.71mm	0.82mm	0.61mm	89.4 arcsec	63.6 arcsec	101.9 arcsec
Requirement HIFI IID-B	0.75mm	15mm	0.75mm	137 arcsec	1)	137 arcsec

(al values ±)
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.

Stability LOU w.r.t. HIFI

	Δx	Δy	Δz	Rx	Ry	Rz
Achievable value 1)	0.008mm	0.008mm 3)	0.001mm	0.17 arcsec	0.12 arcsec	0.57 arcsec
Requirement HIFI IID-B 2)	0.075mm	0.003mm	0.075mm	10.8 arcsec	144 arcsec	10.8 arcsec

All values ±

1) Calculated for LC3-LC1 (steady state analysis)
2) Within 100sec. The very high stability along the y axis should be regarded as a goal (according to HIFI IID-B, issue 2/0)
3) It is expected that due to the high heat capacity of the HSS and the heat capacity of the LOU the goal value of 0.003mm within 100sec. can be achieved

The system level alignment is a vital precondition for a successful Herschel mission. Therefore Astrium is of the opinion that the alignment of the complex cryogenic system can be guarantied only if an end to end verification during TB/TV testing is performed by measurement (as in other projects e.g. XMM). We therefore strongly recommend a camera system which is able to monitor the HIFI / LOU alignment status under TB / TV conditions. In view of the relatively high costs of such a camera system, alternative verification methods will be considered in the future.

10 Abbreviations

AD	Applicable Document
AIV	Assembly Integration Verification
BOL	Begin of Life
CVV	Cryostat Vacuum Vessel
EOL	End of Life
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)
HOWG	Herschel Optical Working Group
H/W	Hardware
I/F	Interface
LOU	Local Oscillator Unit
LMD	Linear Measurement Device
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
TBC	To Be Confirmed
TBD	To Be Determined
WS	Winter Solstice

Quantity	Name	Dep./Comp.	Quantity	Name	Dep./Comp.
	Alberti von Mathias Dr.	ED 544		Reuß Friedhelm	ED 71
	Barlage Bernhard	ED 62	x	Rühe Wolfgang	ED 3
	Bayer Thomas	ED 532		Runge Axel	OTN/TN 94
x	Faas Horst	ED 516		Sachsse Bernt	EC 34
	Grasl Andreas	OTN/TN 64		Sagner Udo	OTN/TN 64
	Grasshoff Brigitte	ED 511		Schäffler Johannes	OTN/TN 64
x	Hartmann Hans Dr.	ED 172	x	Schink Dietmar	ED 522
	Hauser Armin	ED 541	x	Schlosser Christian	OTN/TN 64
	Hinger Jürgen	ED 541		Schwabbauer Paul Dr.	OTN/ED 171
x	Hohn Rüdiger	ED 531	x	Schweickert Gunn	ED 544
x	Hölzle Edgar	ED 171	x	Steininger Eric	ED 522
	Huber Johann	ED 532	x	Stritter Rene	ED 61
	Hund Walter	ED 556	x	Suttner Klaus	ED 542
x	Idler Siegmund	ED 521	x	Tenhaeff Dieter	ED 544
x	Ivády von András	EC 32		Thörmer Klaus-Horst Dr.	OTN/ED 37
	Jahn Gerd Dr.	ED 541		Wagner Adalbert	OTN/IP 35
	Kalde Clemens	ED 513		Wagner Klaus	ED 541
	Kameter Rudolf	OTN/TN 64		Wietbrock, Walter	ED 511
	Knoblauch August	ED 51		Wöhler Hans	ED 544
	Koelle Markus	ED 533		Zipf Ludwig	EC 32
	Kreeb Helmut	ED 541			
x	Kroeker Jürgen	ED 515			
	Kunz Oliver	ED 541			
	Lamprecht Ernst	OTN/TN 72			
	Lang Jürgen	ED 556	x	Pastorino Michel	ASPI Resid.
	Langfermann Michael	ED 531			
	Mack Paul	OTN/TN 64	x	Alcatel (on FTP-Server)	
	Maier Hans-Ulrich	ED 61	x	ESTEC (on FTP-Server)	
x	Mauch Alfred	ED 544			
	Moritz Konrad Dr.	ED 37			
	Müller Lutz	OTN/TN 64		APCO	
	Muhl Eckhard	OTN/TN 64	x	MPE (on FTP-Server)	
	Peitzker Helmut	ED 37	x	RAL (on FTP-Server)	
	Peltz Heinz-Willi	ED 515	x	SRON (on FTP-Server)	
	Peters, Gerhard	ED 533			
	Pietroboni Karin	ED 37			
	Puttlitz Joachim	OTN/ED 37			
	Raupp Helmut	ED 543			
	Rebholz Reinhold	ED 531			