A Technology Review of Large Space Telescopes

(With emphasis on some particular challenges of the ESA Herschel & Planck Telescopes)

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Talk Outline

1. Science mission goals and the derived technical requirements for telescope performance
2. Technological and material system choices made to enable the telescopes to be constructed and tested
3. The metrological challenges and problems encountered in verifying performance
4. Lessons learned

- Herschel Science mission requirements

  - Fourth cornerstone mission of ESA's science 'Horizon 2000' programme – opens last spectral window not yet exploited
  - Performs imaging photometry and spectroscopy in the far-IR and sub-mm (57 to 670 microns) – observe the "**cool universe**"
  - Three instruments: HIFI, SPIRE & PACS
  - Observe and detect objects with BB temps in the 5 to 50K range and gases in the range 10 to a few 100 K with (atomic & molecular) emission lines => star forming regions and Active Galactic Nuclei are of particular interest.
  - AGN's from the early universe are specially targeted, meaning very faint objects at high red-shifts should be detectable

  - Therefore => we need a large cold telescope to catch lots of photons!

  - EXPECTATION => "Discovery potential" is large

• Herschel the Scientific challenge

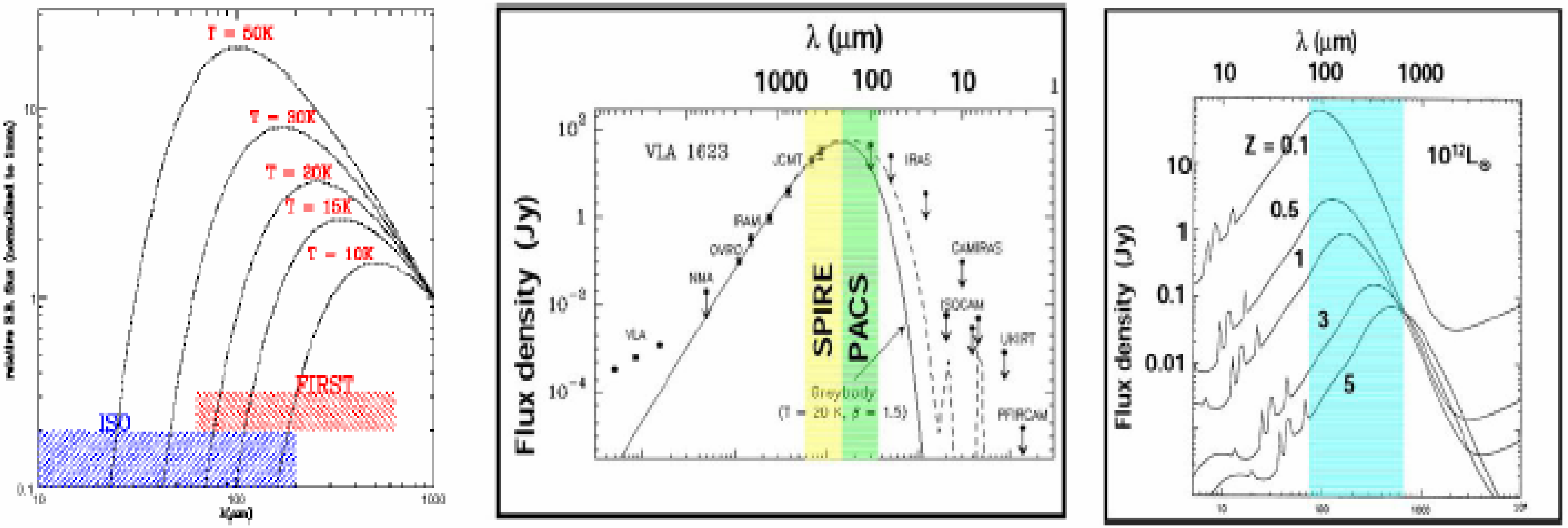
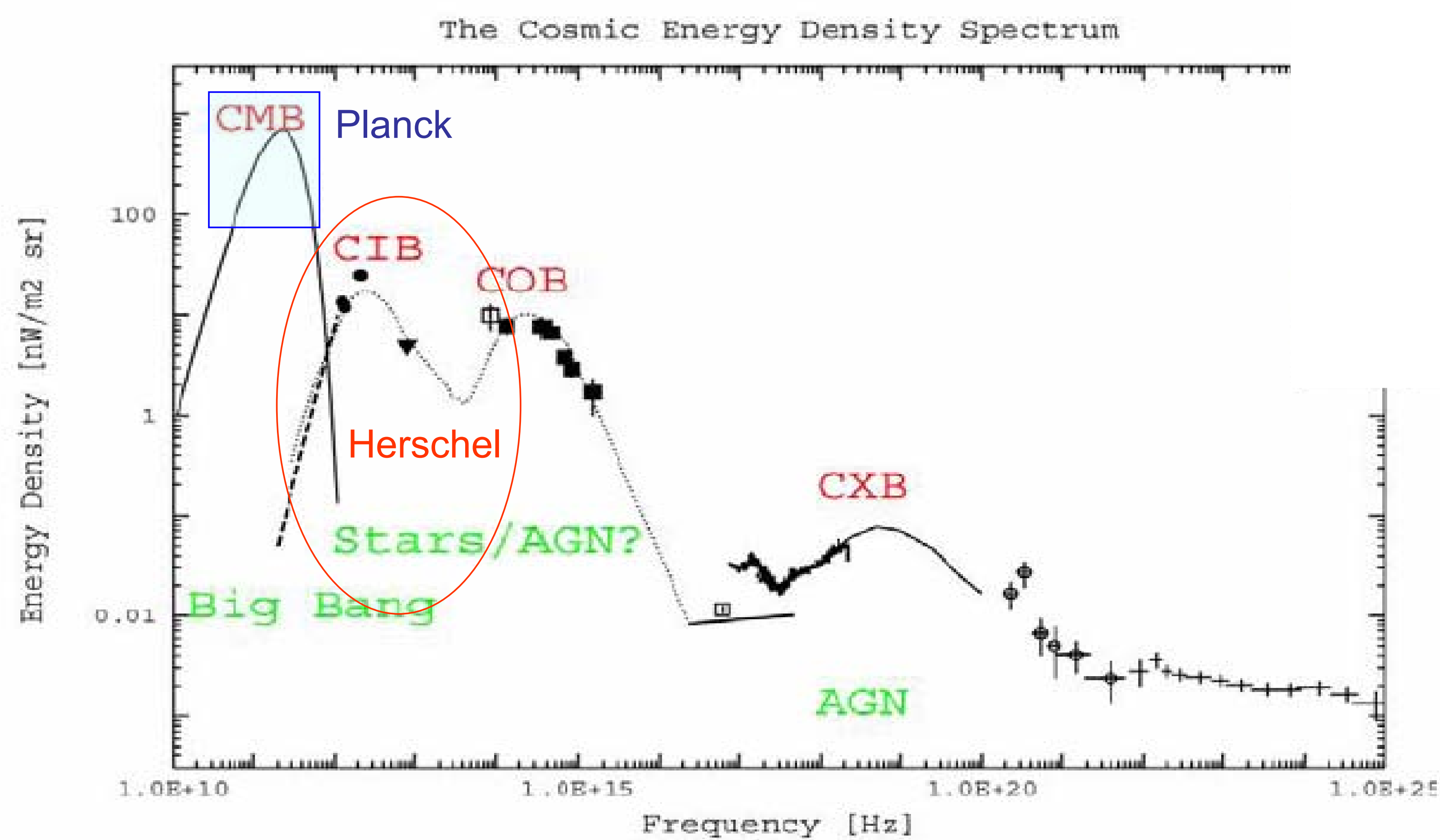


Figure 2. From left to right: *Herschel* will observe cool black (grey) bodies and line radiation from colish gases. The *Herschel* spectral coverage is perfectly adapted to observing the spectral energy densities (SEDs) of young protostars and those of 'typical' infrared dominated star forming galaxies at redshifts from the local universe out to about z~5.

http://www.rssd.esa.int/herschel/.


The Cosmic Energy Density Spectrum
CMB
Planck
CIB
COB
Herschel
CXB
Stars/AGN?
Big Bang
AGN
100
1
0.01
Energy Density [nW/m2 sr]
1.0E+10
1.0E+15
1.0E+20
1.0E+25
Frequency [Hz]

- **Planck Science mission**

  – Planck (formerly called COBRAS-SAMBA) is the third Medium (M3) Mission in the European Space Agency (ESA) long term space science plan “Horizon 2000".

  – Planck is a survey mission to image over the whole sky the temperature anisotropies of the cosmic microwave background radiation with a high sensitivity in the frequency range between 30 and 857 GHz. (Wavelengths 10 to 0.350 mm)

  – The spacecraft carries two instruments to image the sky, one covering 30 to 70 GHz (**LFI**) based on cryogenic HEMT amplifiers, and the second covering 100 to 857GHz (**HFI**) based on bolometers cooled to 0.1 K. A 1.5 m diameter offset telescope focuses the incoming radiation on the focal plane shared by the two instruments.

- Planck focal plane

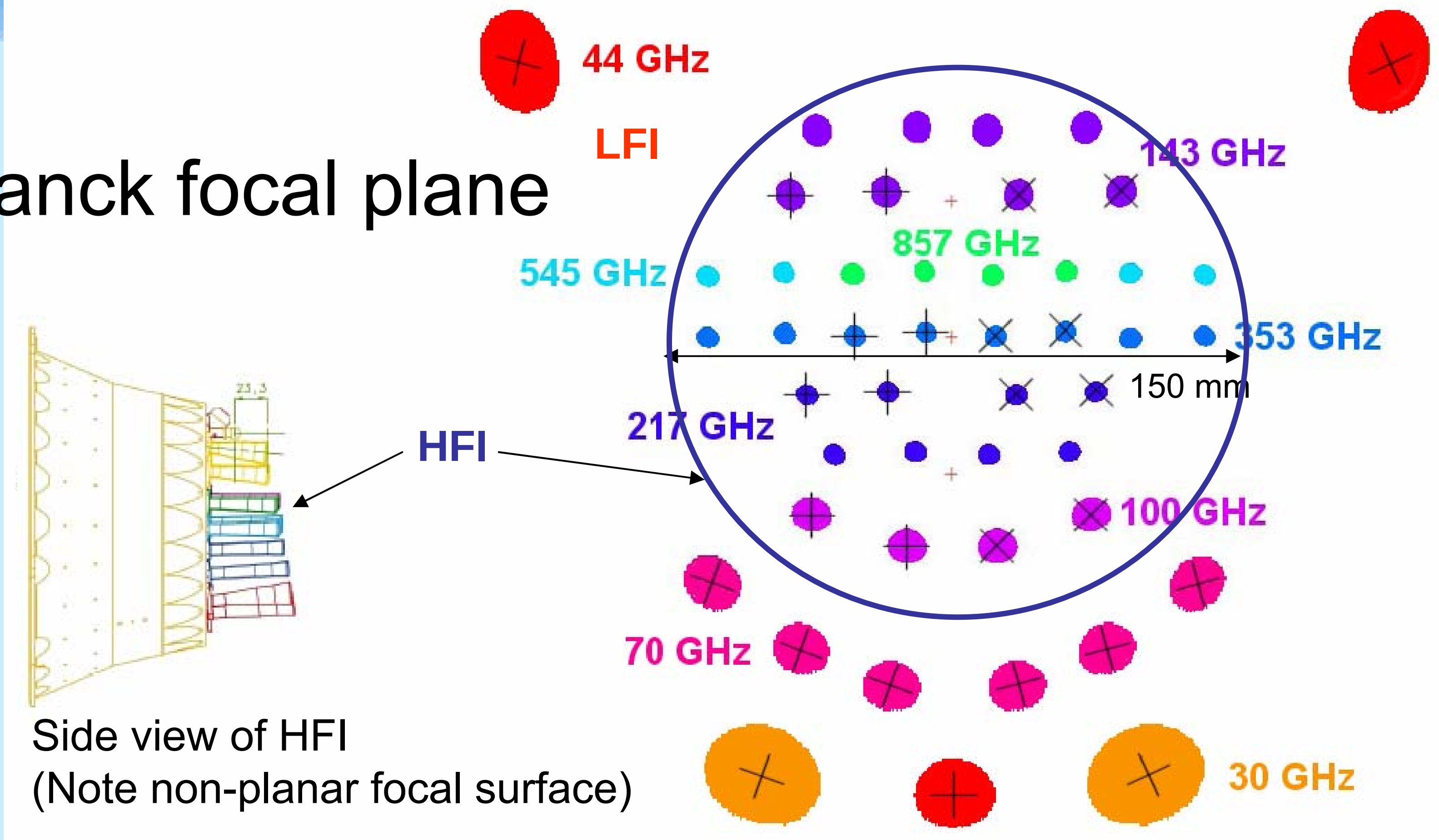


Figure 4.7-2 – Focal plane configuration (including polarisation)

(*Note*: The crosses indicate the direction of polarisation for the polarised horns)

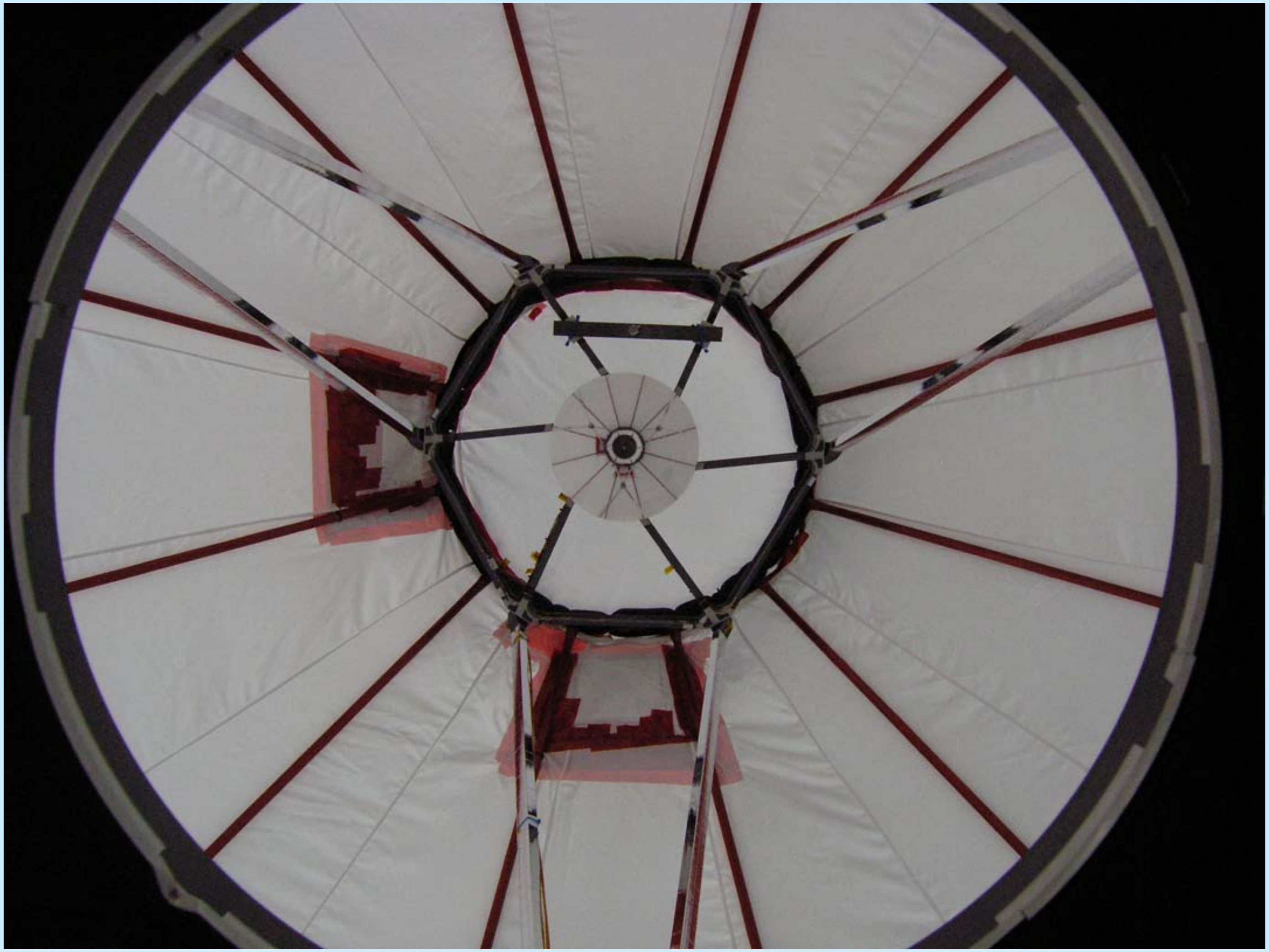
The observational objectives of Planck are:

1. To map over the whole sky the temperature anisotropies of the Cosmic Microwave Background, at all angular scales larger than 10 arcminutes, and with an accuracy set by fundamental astrophysical limits
2. To map over the whole sky all major Galactic and extragalactic sources of emission at the wavelengths measured by Planck
3. To characterise the polarisation state of the CMB (goal) – *Has never been done before!*

- To achieve the scientific objectives of Planck it is required that the payload instruments fulfil the following essential requirements :

  - The **angular resolution** achieved must be of order 10' or better at the frequencies where the (CMB) Cosmic Microwave Background signal is dominant (i.e. between 100 and 350 GHz). This requirement sets the size of the effective aperture of the telescope to be of order 1 meter in diameter. Furthermore, the
  - Planck instruments must sample the sky with a spatial frequency compatible with the final 10' resolution => Horn spacing & rot. rate
  - The **frequency coverage** must be wide enough to provide robust removal of the foregrounds.
  - The **sensitivity** must be sufficient for adequate detection of the CMB anisotropy (i.e $\Delta T/T < 2 \times 10\text{-}6$).
  - **Systematic effects** must be maintained at a level such that they do not add significantly to the instrumental sensitivity. The main sources of unwanted signal are: straylight (both due to celestial sources and to self-emission), thermal variations and interference due to the TM/TC system.

Herschel telescope design



• Herschel telescope requirements

- As large as possible (largest space telescope to date !)
- As cold as possible 70K (for low emissivity) – passive cooling
- As lightweight as possible (0.1 areal density of Hubble = 30 kg/m^2)
- As stable as possible (thermal & mechanical)
- Fixed focus (no mechanism risk at cryo) => “a-thermal” performance if possible [Build at ambient & operate at cryo]
- Diffraction limited optical performance at < 90 microns (< 6 micron WFE rms)
- FOV 0.25 degree
- Optimised for minimum straylight
- Must survive launch loads

- Verification on ground at operational temperature, under vacuum and with gravity offloading (PM sags under it’s own weight)

- **Herschel chosen design:**
  - Cassegrain (original concept RC)
  - 3.5 m diameter primary
  - Pupil on secondary (for stability)
  - Anti-narcissus cone integrated into secondary
  - Material system SiC 100 (sintered)
  - Construction – modular from 12 petals & components
  - Made to approx shape, ground & polished with diamond tooling
  - Coating – Al & Plasil protective layer

• Detailed Herschel Telescope design specs

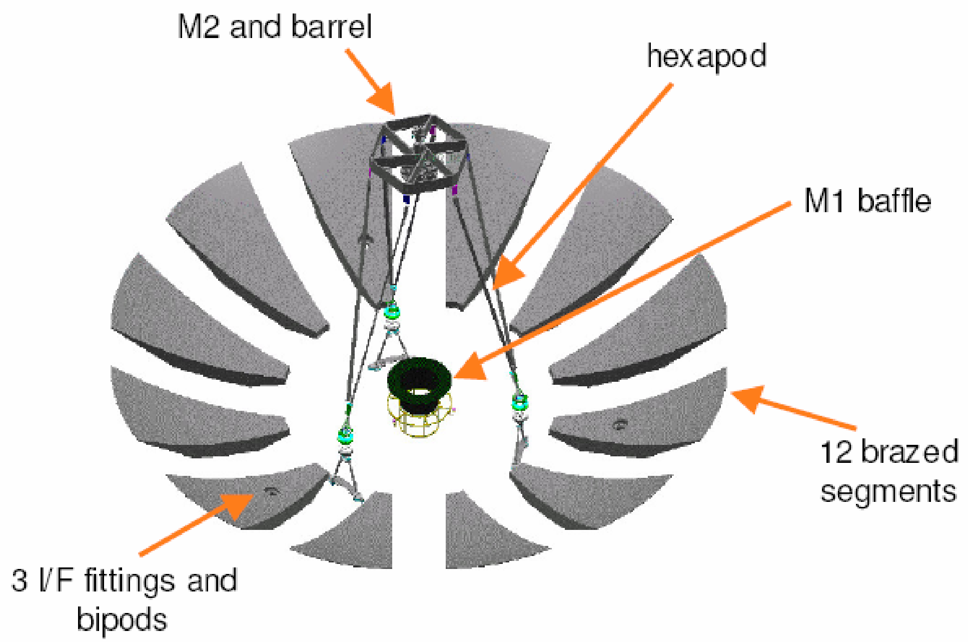


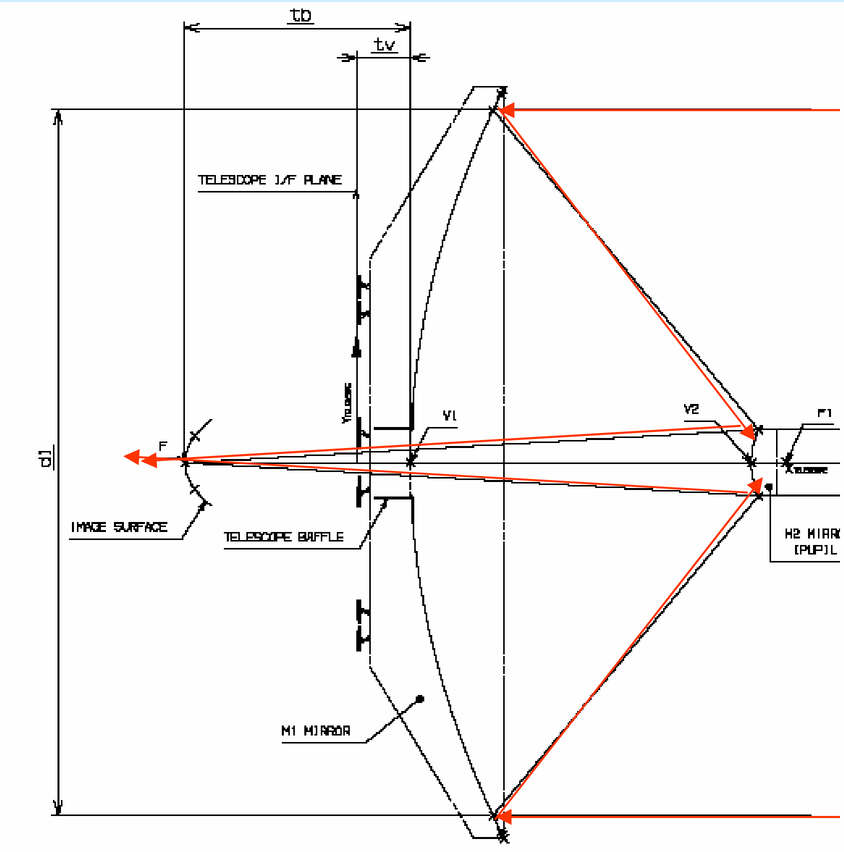
Figure 2-3: Exploded view of the Telescope

Primary reflector		
Radius of curvature	*3500 mm*	*± 2 mm (*)*
Conic constant	*-1*	
f-number	*f/ 0.5*	
(Free) diameter	*3500 mm*	*0, +2 mm(*)*
Secondary reflector		
Radius of curvature	*345.2 mm*	*± 0.4 mm (*)*
Conic constant	*-1.279*	*-*
Diameter	*308.1 mm*	*± 0.2 mm*
Image surface		
Radius of curvature	*- 165 mm*	*-*
Conic constant	*-1*	*-*
Diameter	*246 mm*	*-*

Focal length = 28.5 m (+/- 150 mm), f/no = 8.68 (+/- 0.02), Transmission 0.975

And the KILLER sensitivity => longitundinal magnification = 200 (10µm M2 = 2 mm delta focus)

• Telescope optical ray trace



Herschel Telescope optical parameters	Cassegrain theoretical	293K As built	70K As built
Primary reflector			
Radius of curvature	3500 mm	3490.4 mm	3489.619 mm
Conic constant	-1	-1.000011	-1.000011
Distance to M2	1587.998 mm	1583.950 mm	1583.561 mm
Secondary reflector			
Radius of curvature	345.2 mm	343.568 mm	343.488 mm
Conic constant	-1.279	-1.27760	-1.27760
Diameter	308.12 mm	307.982 mm	307.910
Image surface			
Radius of curvature	-165 mm	-166.7 mm	-166.7 mm
Conic constant	-1	-1	-1
Diameter	246 mm	245 mm	245 mm
Distance to M1	-1050 mm	- 1048.06	-1059.97 mm

• Telescope defocus sensitivities

With Code V :

Parameter	Variation	Relative Defocus
Curvature R1	1mm	+105.637 mm
Curvature R2	0.1 mm	- 9.370 mm
Inter-mirror V1V2	0.01mm	-2.11 mm

Formula of geometrical optics can also be used as a <u>roof approximation</u> :

Paramètre	formule	Variation	Défocus relatif
Courbure R1	$0.5\ Gy^2 dR1$	+ 1mm	+132.2 mm
Courbure R2	$-2(S2F/R2)^2 dR2$	+ 0.1 mm	- 9.57 mm
Inter-miroirs V1V2	$-4f^2.E/(R1R2)dE$	+ 0.01mm	- 2.6 mm

• Herschel spacecraft

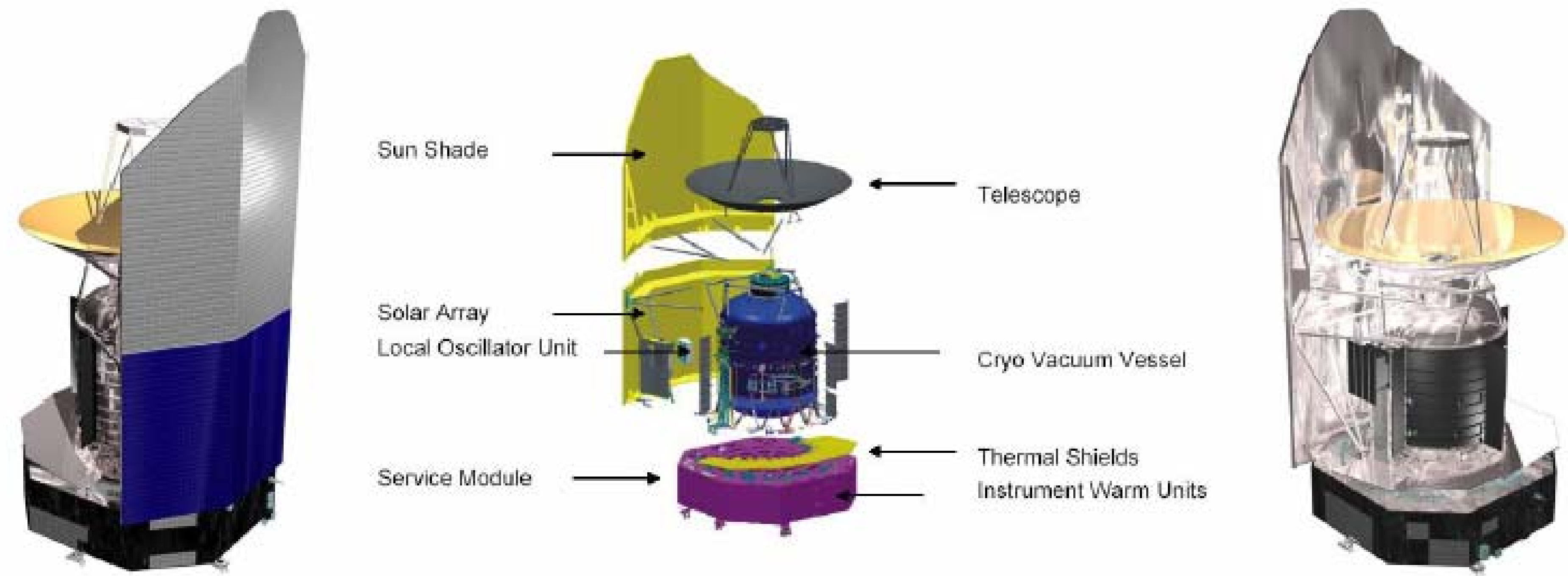
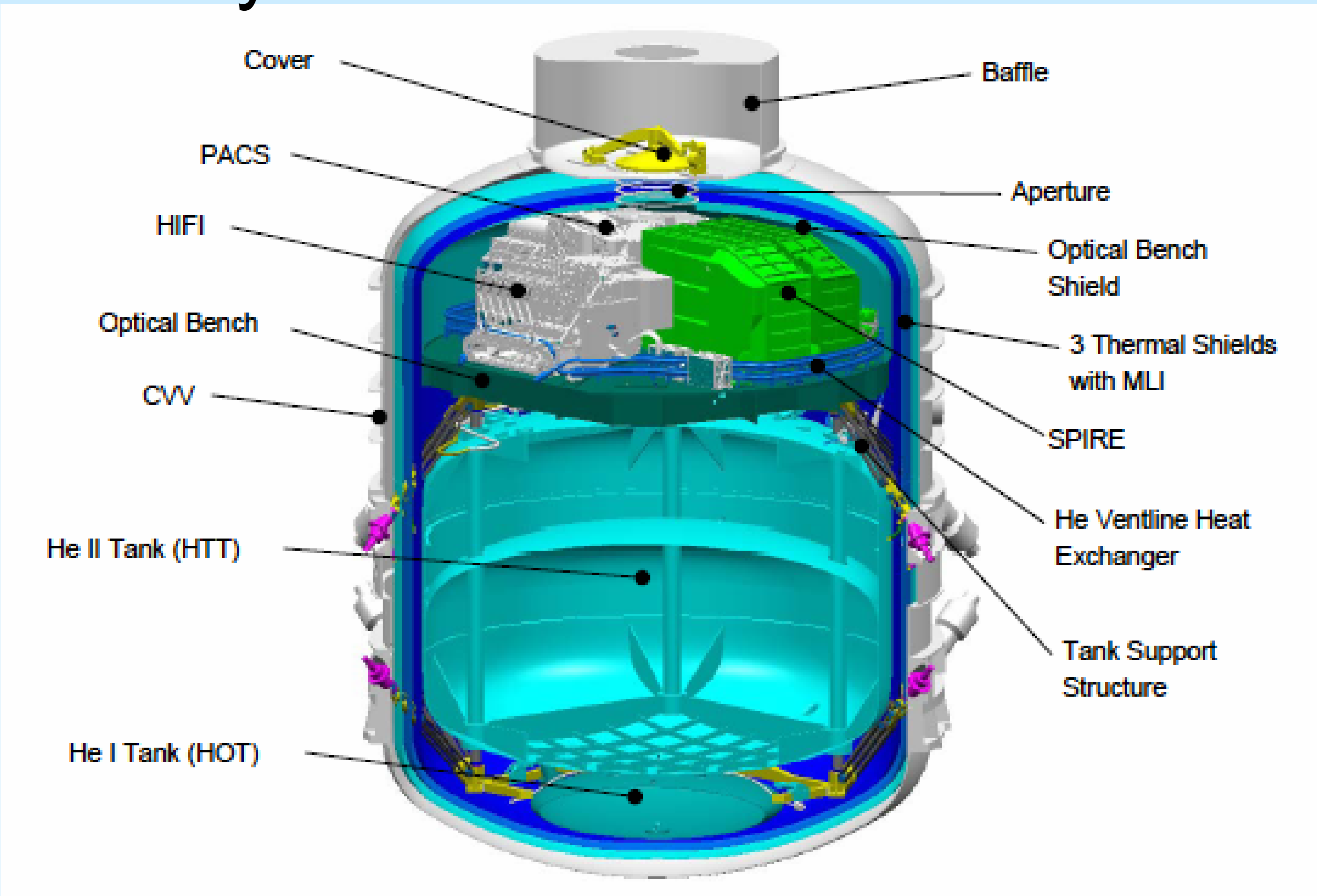
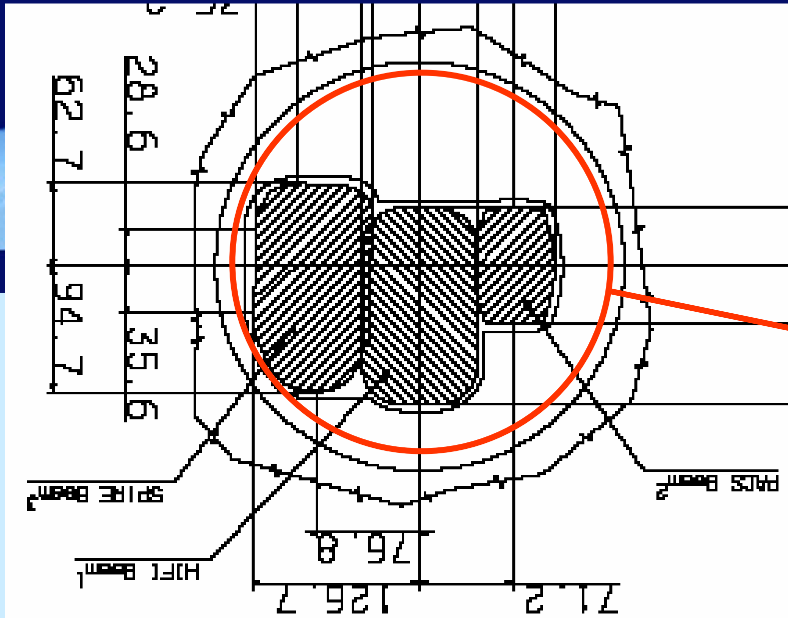
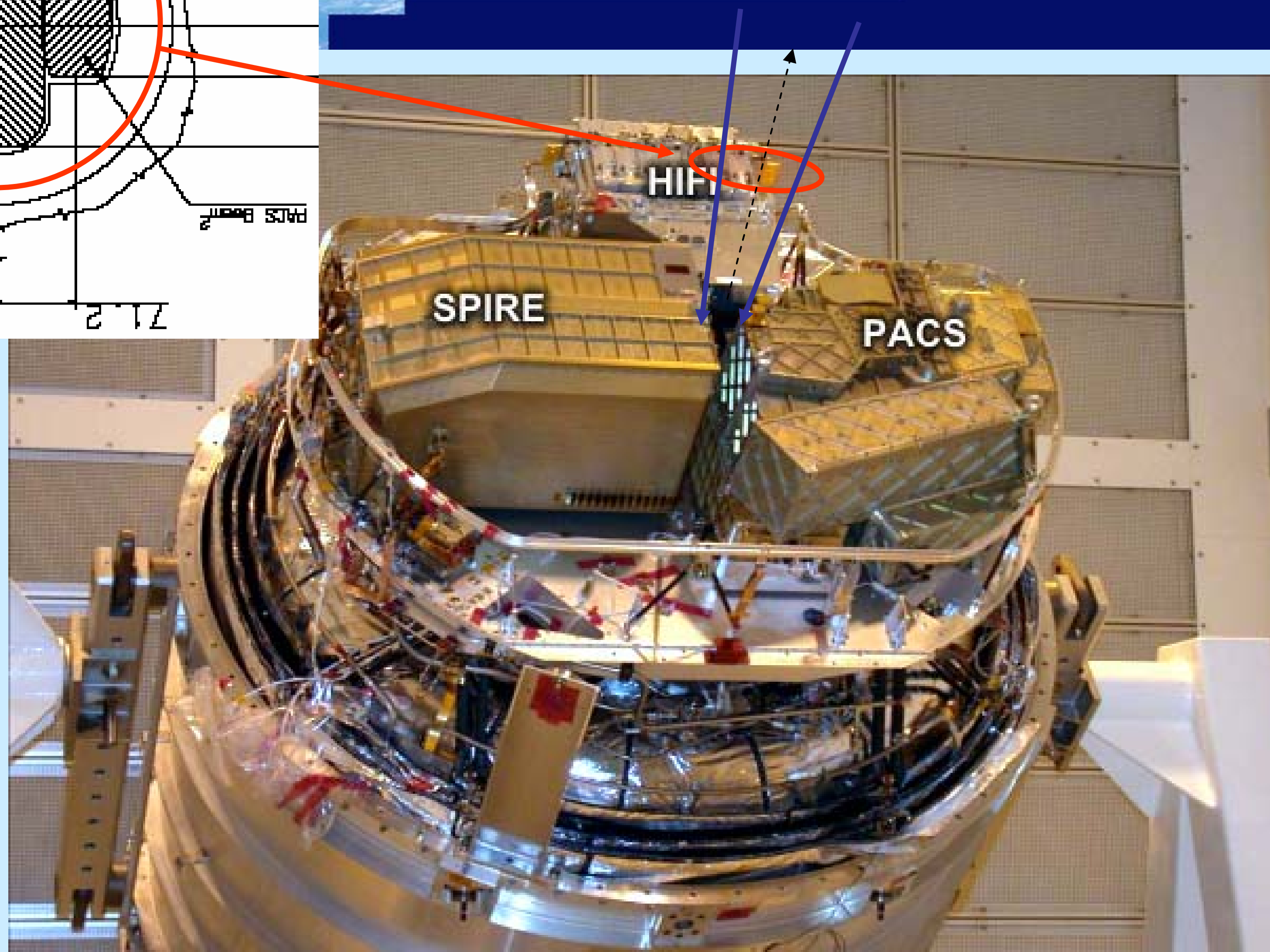


Figure 4. The *Herschel* spacecraft has a modular design. On the left facing the 'warm' side and on the right facing the 'cold' side of the spacecraf, the middle image names the major constituents. Approximate vital data include a launch mass of 3200 kg, height 7.5 m, width 4 m, and power 1500 W. It is designed to offer 3 years of routine science operations.

- Herschel cryostat & instruments

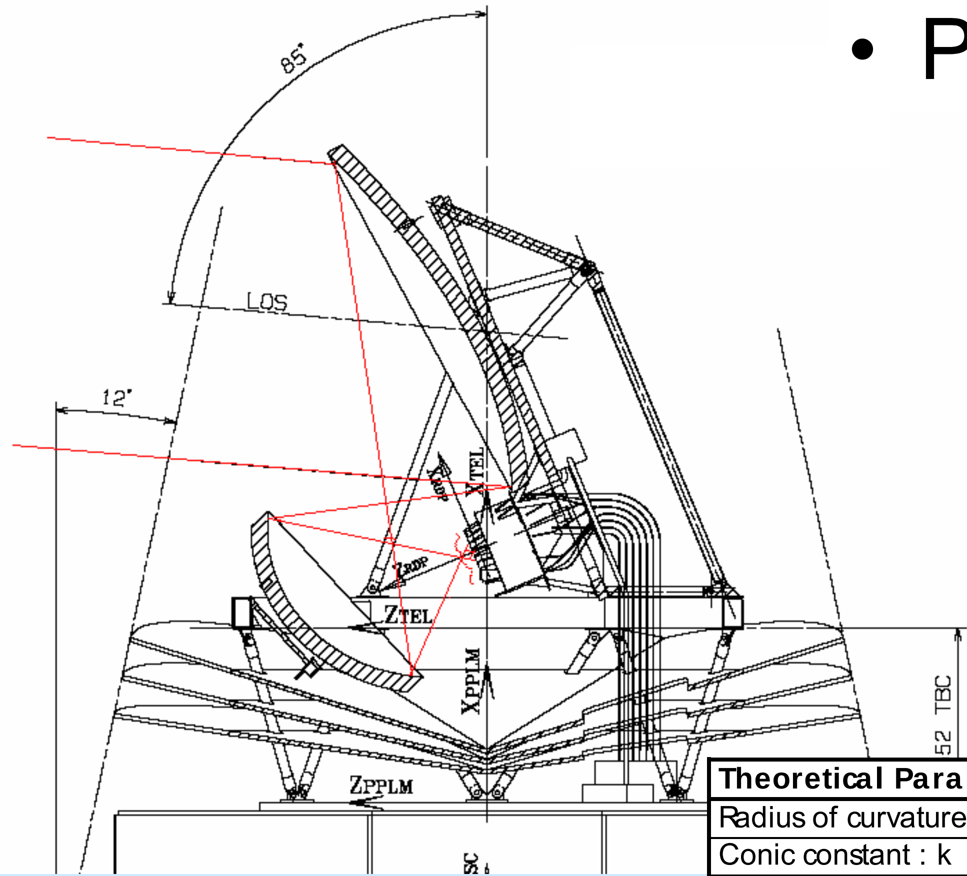






Herschel instruments and focal plane layout.
Only HIFI has a pixel on-axis.

• Planck telescope design

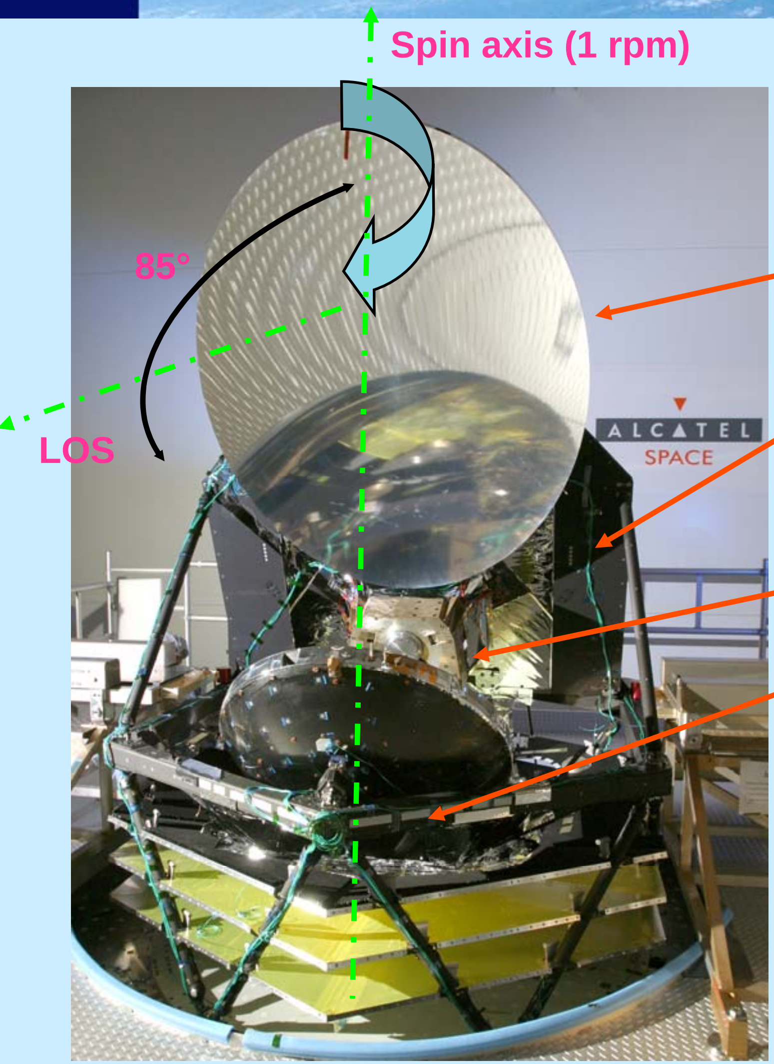


Aperture	1.5m off-axis
Focal length	1600mm
Field of view	+ / -5°
Line of Sight	At 85° of Xtel

Off axis Gregorian concept, satisfying the Dragone-Mitsugushi condition for supression of cross polarisation effects.
Main drivers:
Unobscured aperture & straylight.

Theoretical Parameters	PR	SR
Radius of curvature of the ellipsoid: R (mm)	1440.000	- 643.972
Conic constant : k	- 0.86940	- 0.215424
Focus to vertex distance (mm)	745.18	-439.9
Interfoci distance (mm)	20562	-762.0

Planck flight model telescope



• Planck Telescope main design features

– Reflectors provided by ESA/DSRI (manufacturing by Astrium, Friedrichshaven)

– Telescope structure – Contraves (CH)

– Baffle

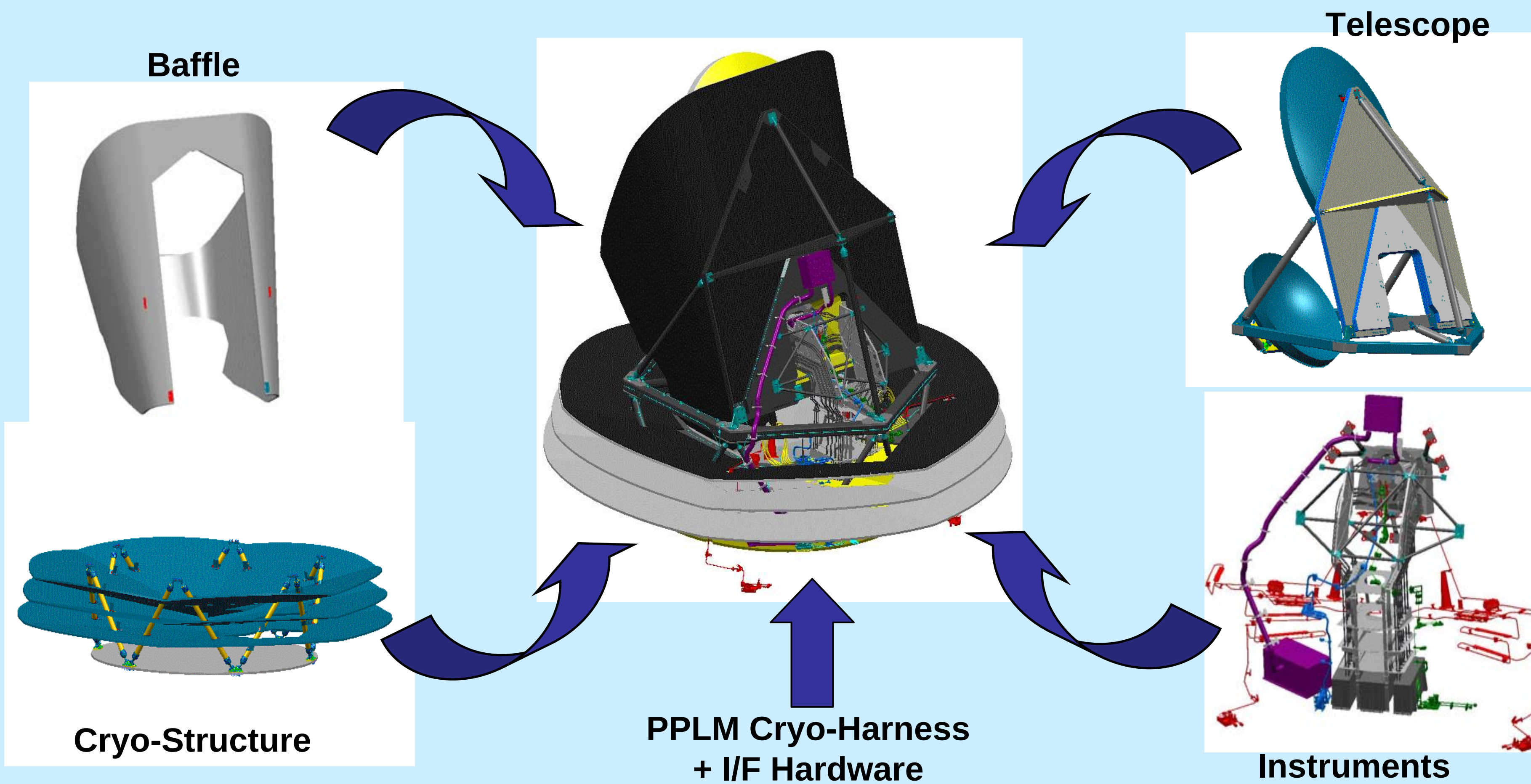
– FPU (IAS, Paris & Laben Italy)

– Mechanical IF with the S/C

↳ LOS orientation wrt spin axis leads to a non classical telescope architecture (PR at a high position wrt the Cog) : 6 interface points are required to withstand the mechanical loads.

↳ Cryo-structure/telescope Interface loads is one of the major contributors to the telescope performance budget

- PLANCK PAYLOAD MODULE ARCHITECTURE OVERVIEW

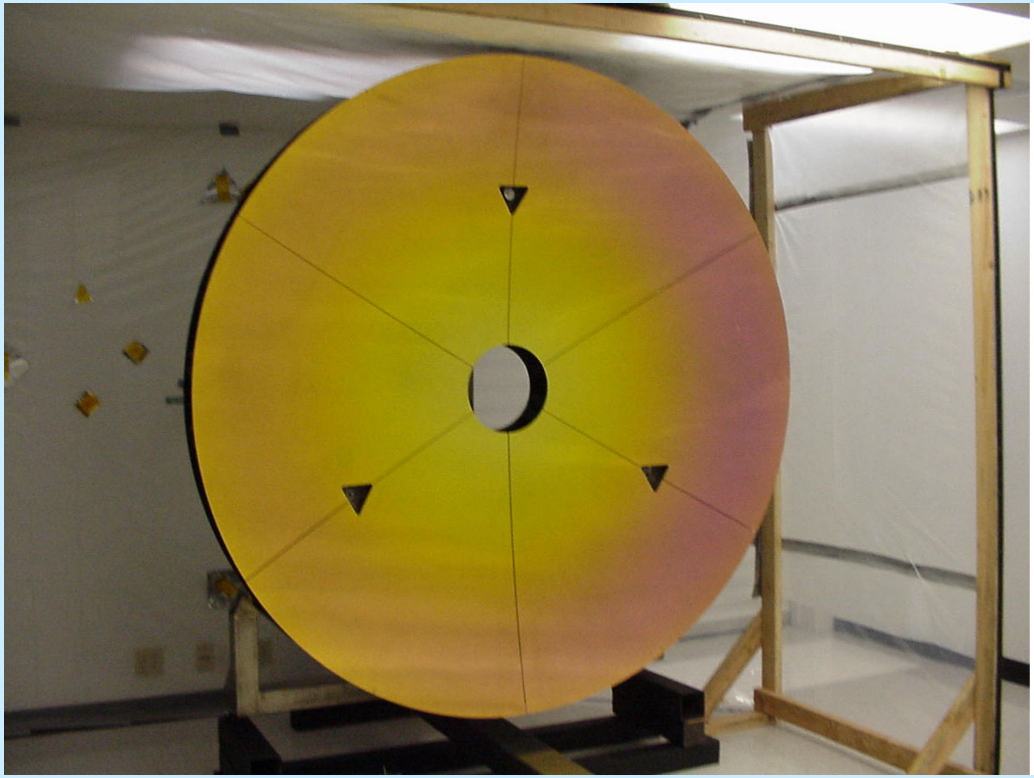


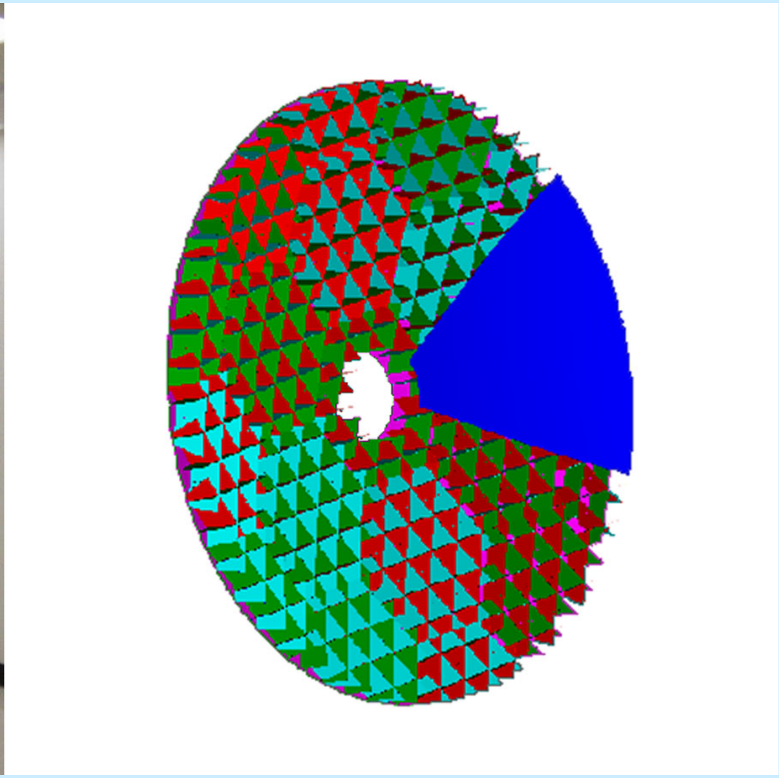
- **Herschel telescope technology**

  – Original plan was to have a NASA supplied CFRP telescope. 2m demonstrator built by COI (San Diego) – did not quite reach the specs, but was close. NASA eventually pulled out of programme for financial reasons.

  – Backup technology development run in parallel by ESA in phase A/B, using Astrium-Boostec SiC 100. A 1.35 m spherical mirror was realised and successfully tested to qualify the material and process.

  – SiC was therefore chosen for implementation at kickoff of Phase C/D





NASA-JPL, COI 2 m CRFP Lightweight Demonstration Mirror (10.1 kg/m^2)

9.47 kg	M2 barrel
0.49 kg	Hexapod tilt
2.87 kg	M2
7.19 kg	Hexapod
3.61 kg	Hexapod fittings
5.81 kg	Hexapod I/F
267.84 kg	M1
2.5 kg	SLI's
5.82 kg	Bipod fittings
4.66 kg	Bipods
3.99 kg	Stand off

TOTAL : 314.3 kg

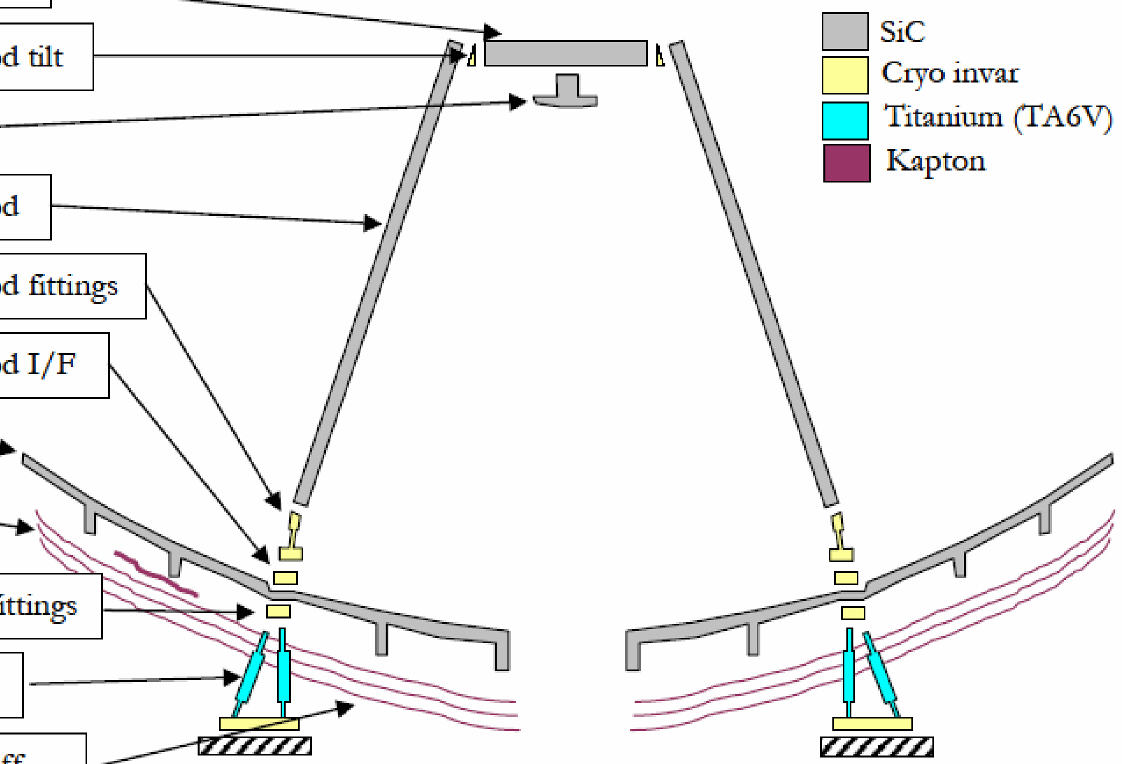
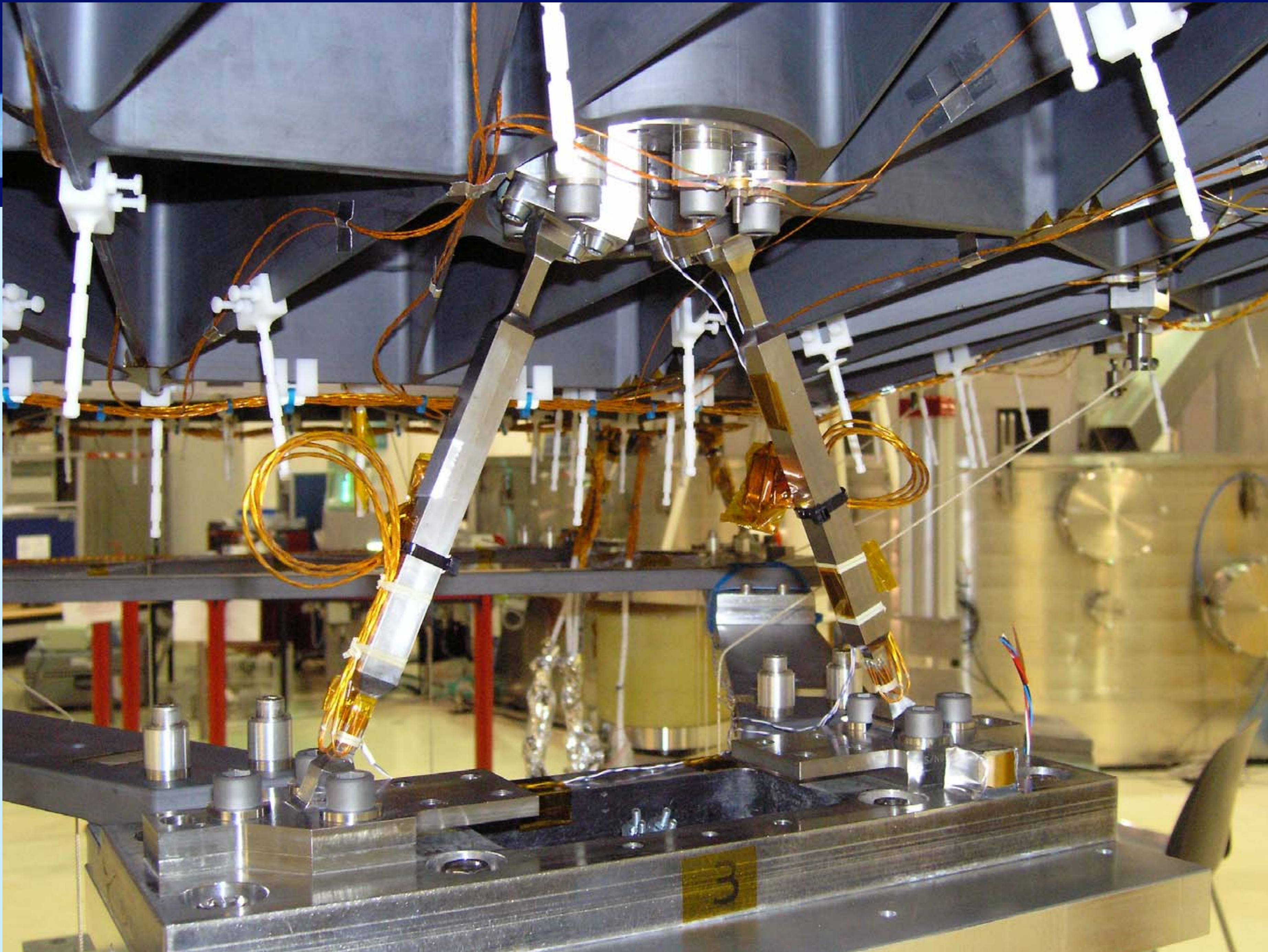


Figure 5.2.a : Mass distribution in the thermal model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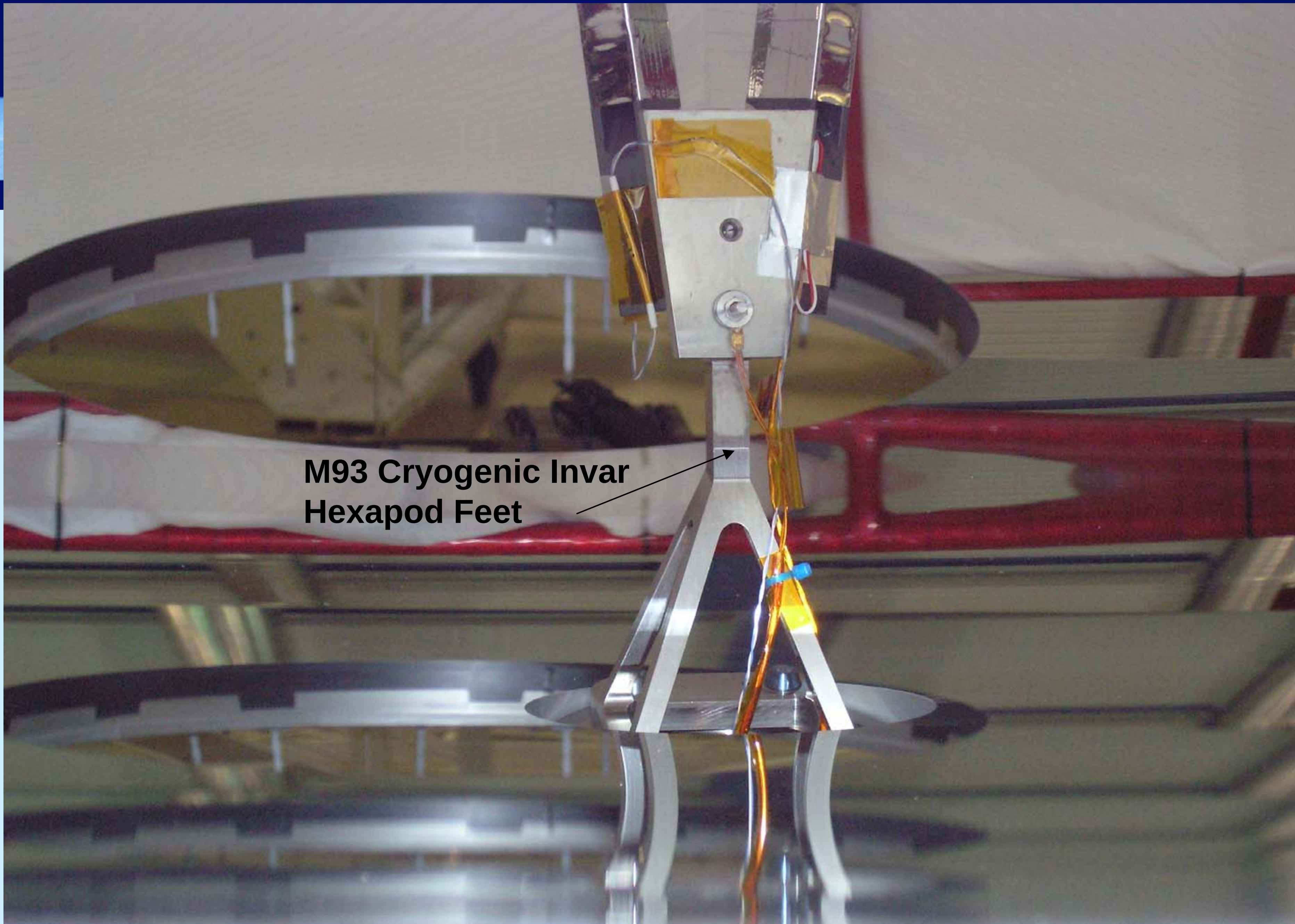

M93 Cryogenic Invar
Hexapod Feet

• Herschel telescope performance WFE budget

Telescope WFE Performances Objectives : System WFE < 6 µm RMS (FOV)			Specif. Ed 7	Goal	Performances	Total WFE centered	Total WFE FOV	Strehl
total WFE	TEPE-050		6				5,51 C	0,85
WFE on-axis , with defocus			5,5			4,8 C		
WFE (BF)	best focus and on-axis	µm	5,0		4,8 C			
Focus	TEPE-150	mm	5	3	0,0 C		I/Fadditive shimming	8,6
Foc.Dec.Y	TEPE-150	mm	5	3	-0,1 C			
Foc.Dec.Z		mm	5	3	0,5 C			
Pupil Dec.Y	TEPE-160	mm	3	2	-0,5 C			
Pupil Dec.Z		mm	3	2	-0,7 C			
focus kno.	TEPE-155	mm	3	2	3,0 C			
Foc. D. kno.	TEPE-155	mm	3,5	2	3,1 C			
Pup. D. kno.	TEPE-160	mm	1	0,5	0,5 C			
Focal length	TEPE-065	mm	150	error	123 C			
			90	know	76 C			
LOS orientation	TEFU-007	mrd	3		0,02 C			
LOS orientation kno.		mrd	2		0,1 C			

- tested
- computed with FEM or thermal model
- no contribution
- computed from other data
- allocation

earth curvature effect	gravity compens error	measured Ambient on axis	measured ambient FOV	Telescope Cool down (70 K)	Launch effect	flight thermal map	integration on PLM	PLM cool down	In orbit distorsions from SSL

- **Herschel telescope metrology**
  - Dilemma; measure & verify performance with “good enough” accuracy under both room temp & cryogenic vacuum conditions (70 K).
  - Cool telescope efficiently without disturbing metrology tools
  - 3.5 m diameter auto-collimation mirror? BIG problems: Cost, Lead time, Manufacture, Calibration and thermal stability verification.
  - Decision: Use liquid mirror.
  - Choice: Interferometry or Hartmann
  - Decision: Hartmann => 2 steps 1) Full resolution (64 x 64 or 48 x 48) absolute WFE map @ ambient, 2) Low resolution (8 x 8) Delta WFE at cold temps. (with Leica Laser Tracker for WFS position measurements)
  - Major assumption => no high spatial frequency components induced (or changed) during cooldown.

Key Telescope Focal Surface Alignment Requirements

TEPE-150

The actual on-axis point of the best focus shall be positioned and located within a cylindrical tolerance volume perpendicular and centred on the X-axis of the telescope. The volume of the cylinder shall be ± 5 mm (with a goal of 3 mm) in cylinder-axis (X-direction) and ± 5 mm (with a goal of 3 mm) in diameter.

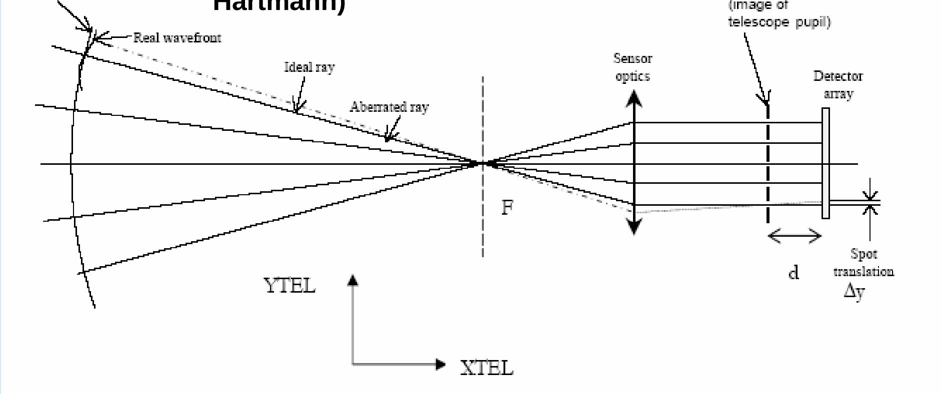
TEPE-155

The centre of the telescope field of view in the focal plane shall be known with respect to this reference frame with an accuracy of ± 3.5 mm in lateral direction and ± 3 mm (defocus) in axial direction (with a goal of ± 2 mm).

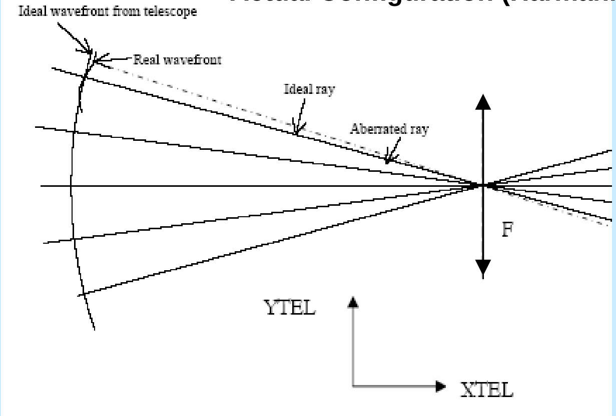
Herschel Telescope Specification
Reference: SCI-PT-RS-04671 Date: 26 July 2004
Issue/Rev. No: 7/0

- WFS Determines Focal Plane and Aberrations
- Rigid Body Measurements are used to
  - Ensure Telescope angular alignment
  - Measure Distance from Focal Point to Telescope I/F

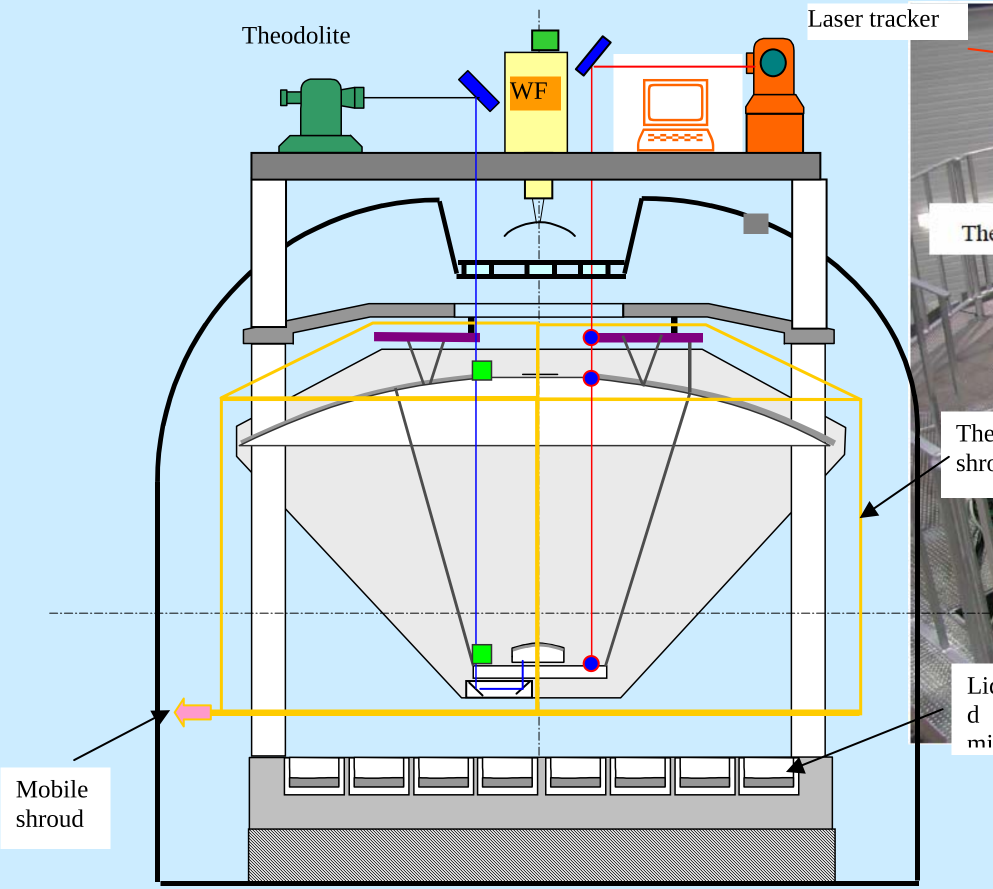
Standard Configuration (Shack-Hartmann)

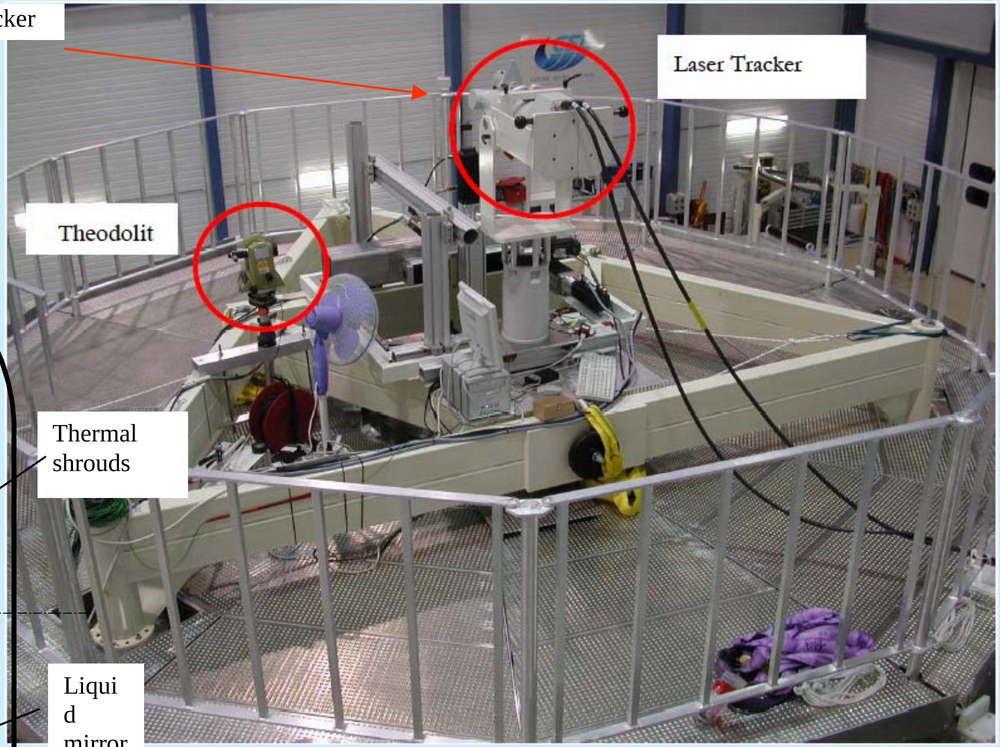


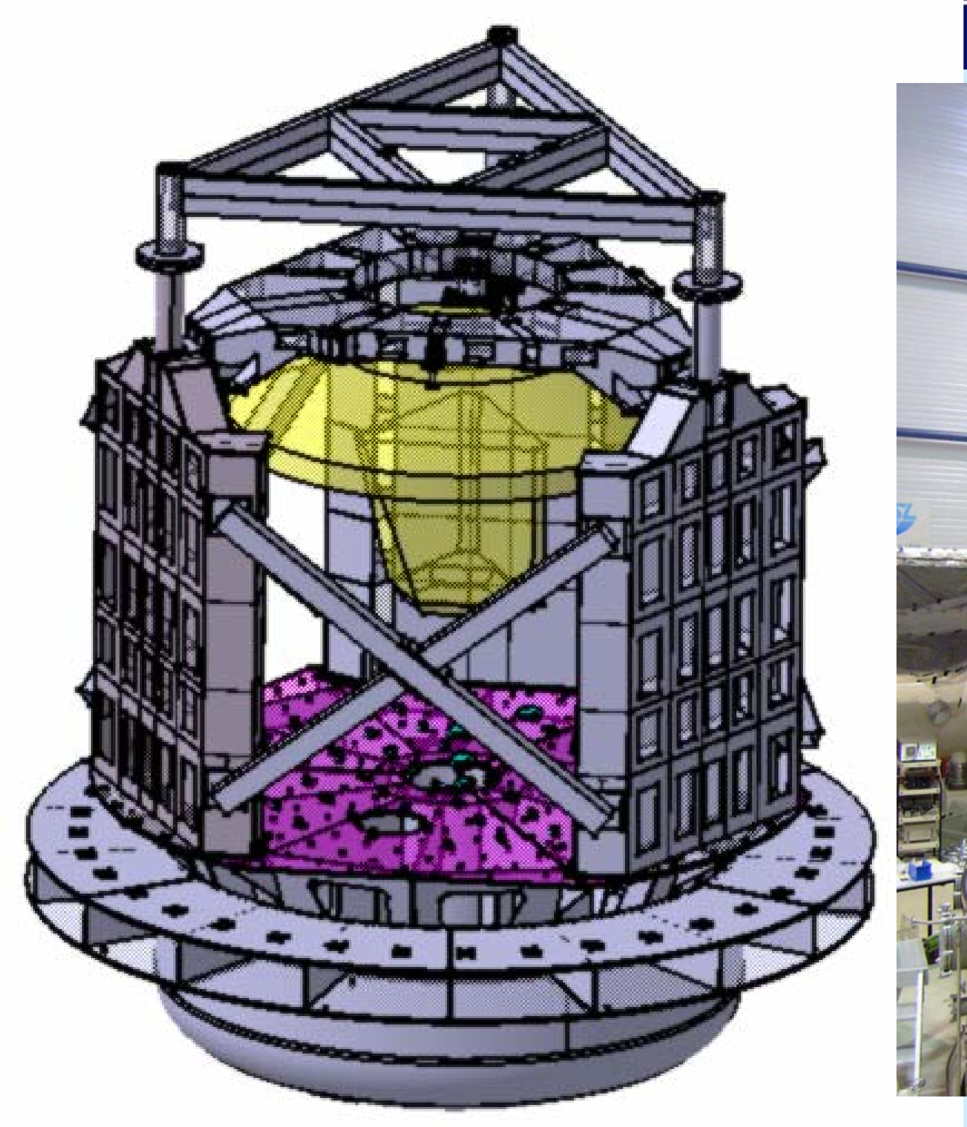
Actual Configuration (Harmann projection only)

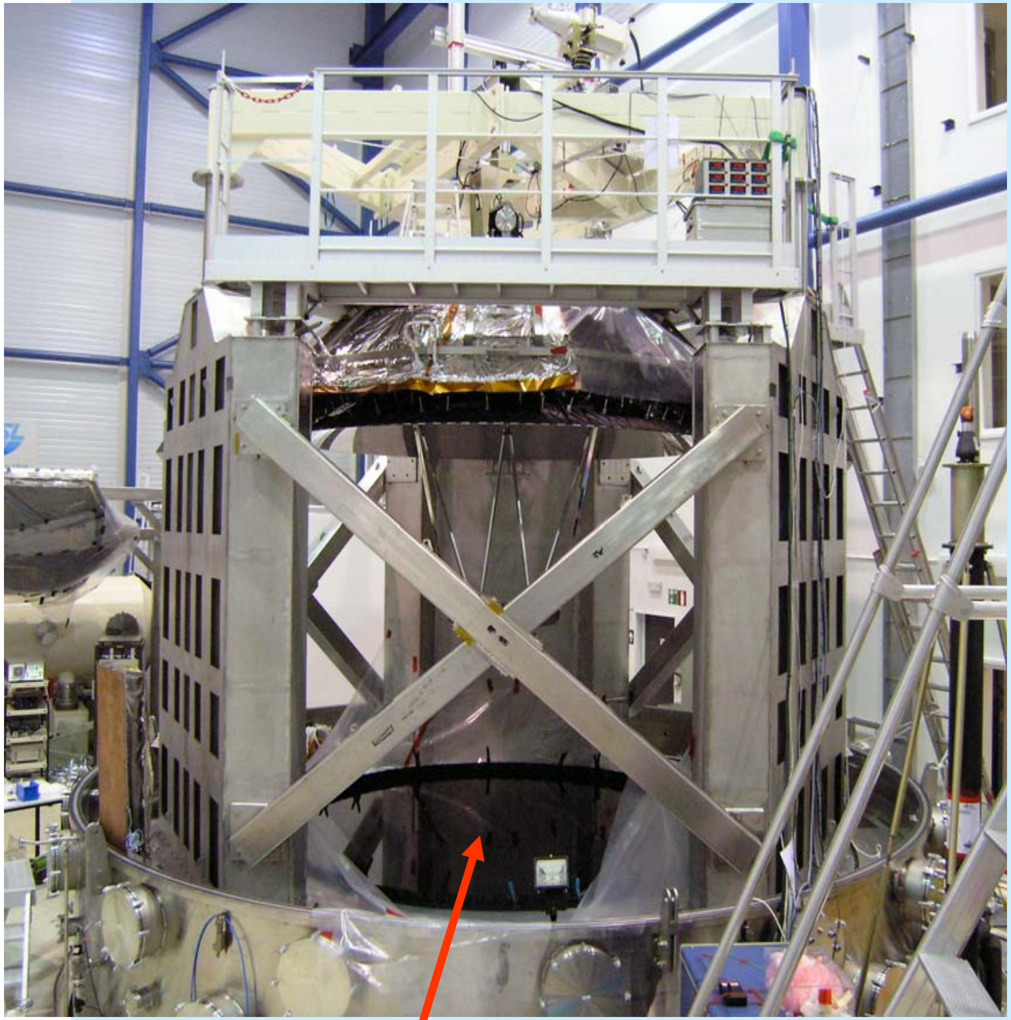


• Herschel telescope test metrology





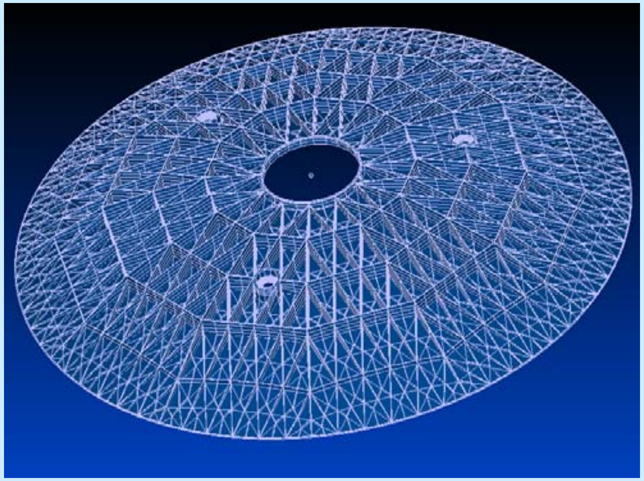


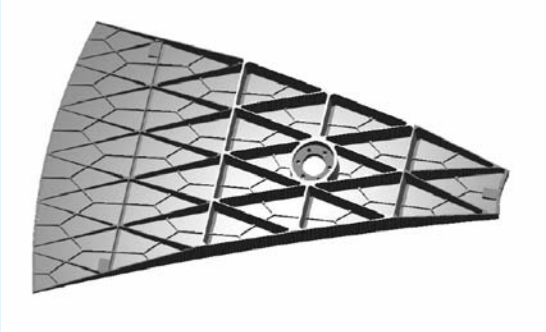


Liquid mirror (“piscine”)

Herschel Telescope Primary structure is complex

- Structural Cells
  - 420 Total (different distribution radially and tangentially)
- Polishing/Cryo-Quilting
  - Can Result in Mid/High Spatial Freq Errors
  - Recommended Sampling: 5 x 5 Points/Cell
- Full Aperture Sampling Would Require
  - 420 x 5 x 5 = 10500 => 116 x 116
- Compromise needed between optical and thermal needs
  - Large no of apertures makes cooldown inefficient and unstable
- HSM High res mode at ambient
- LSM Low res mode at cryo

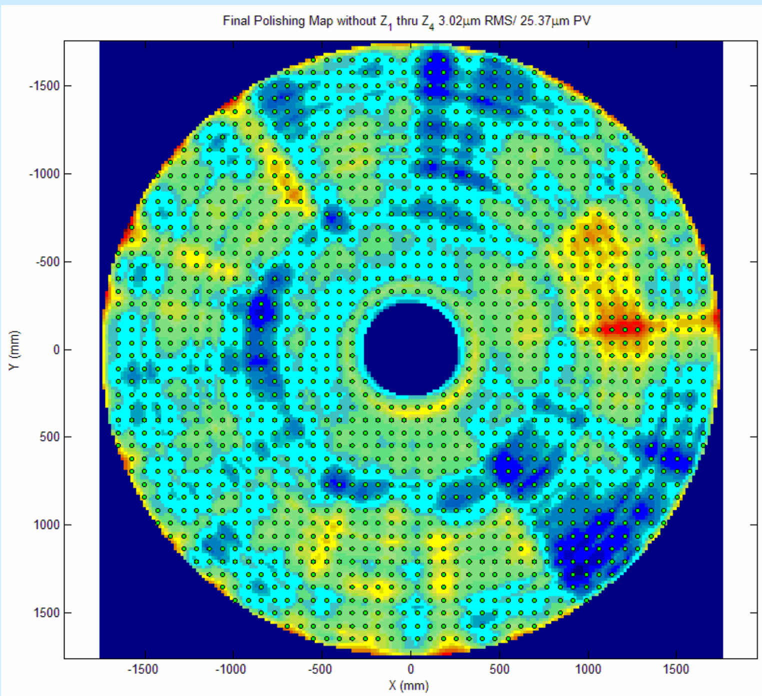




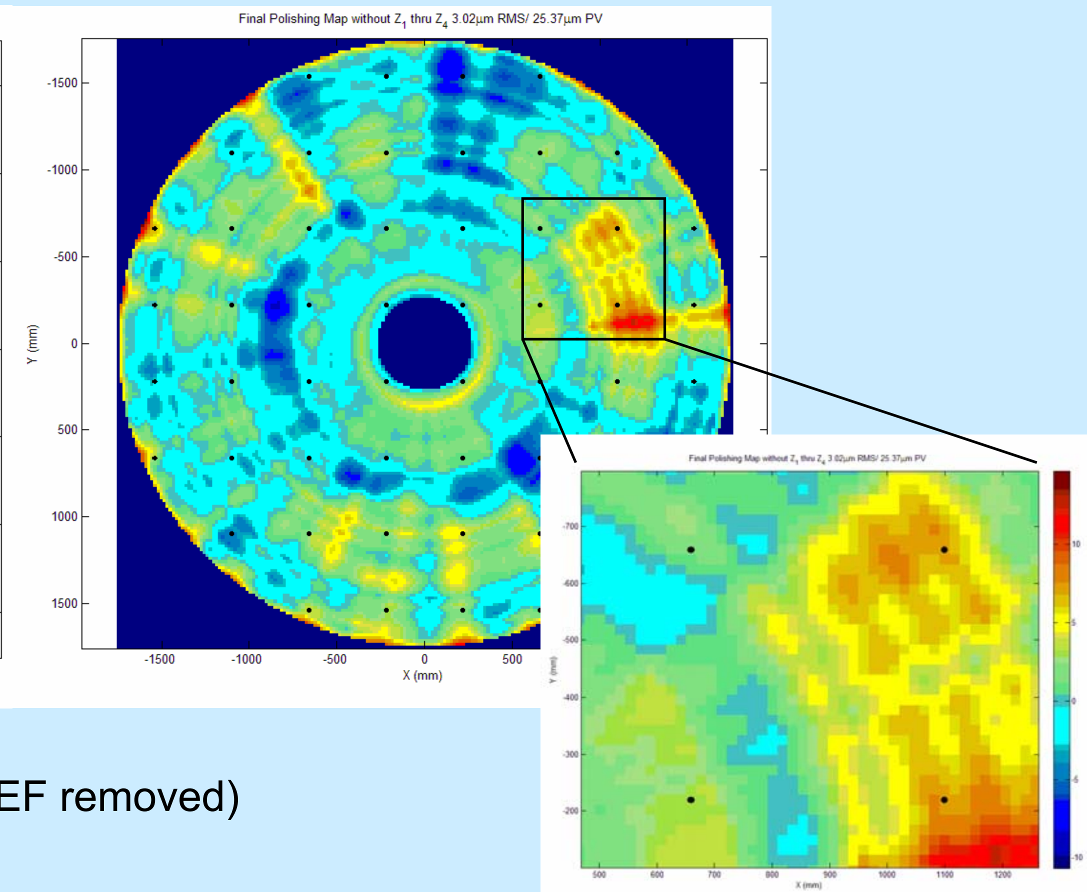
liquid mirrors are aligned on optical bench inside the chamber

Spatial resolution of the measurement: HSM versus LSM

HSM



LSM

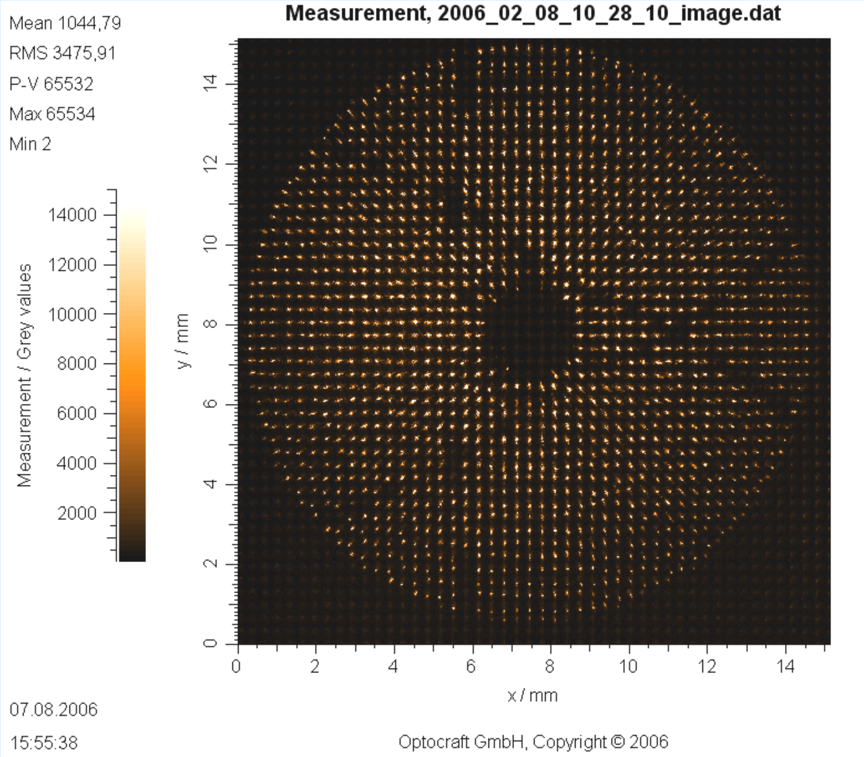


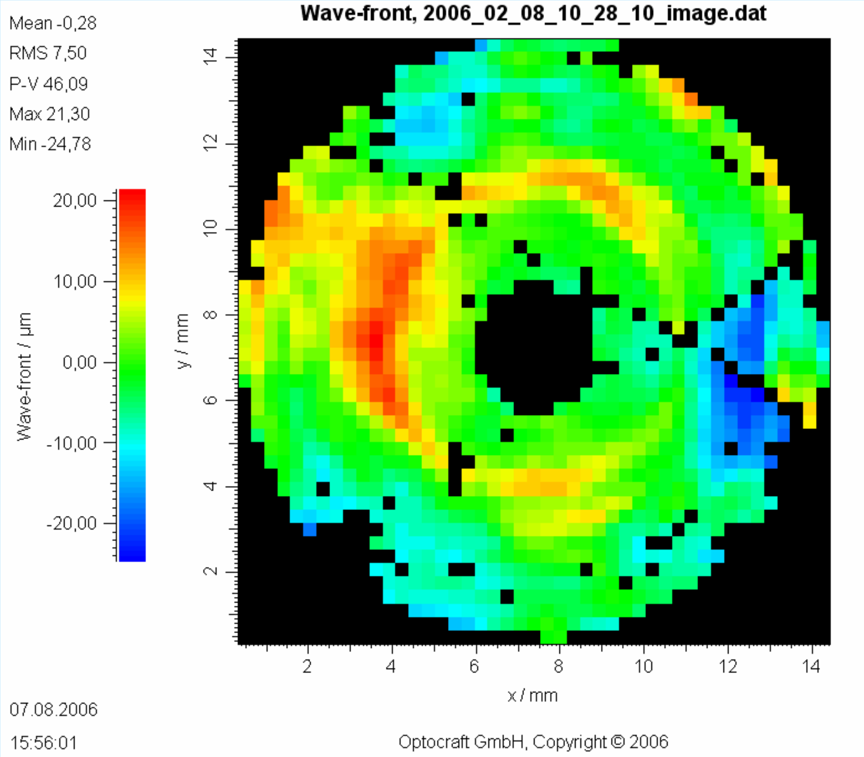
Polishing map (TLT, DEF removed)

Lateral resolution: HSM

Camera frame

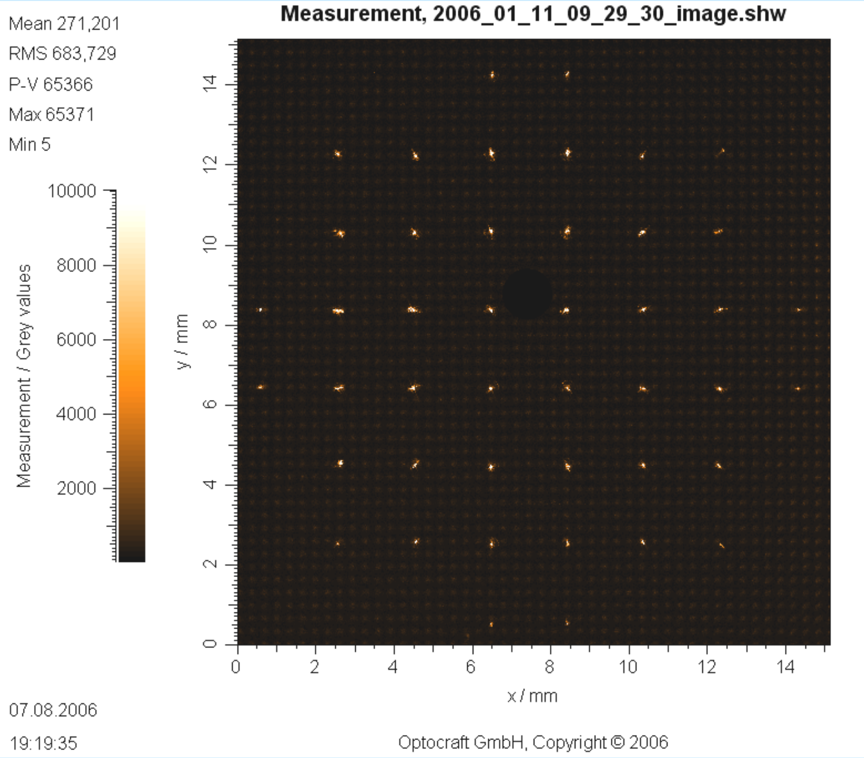
Pure wave-front



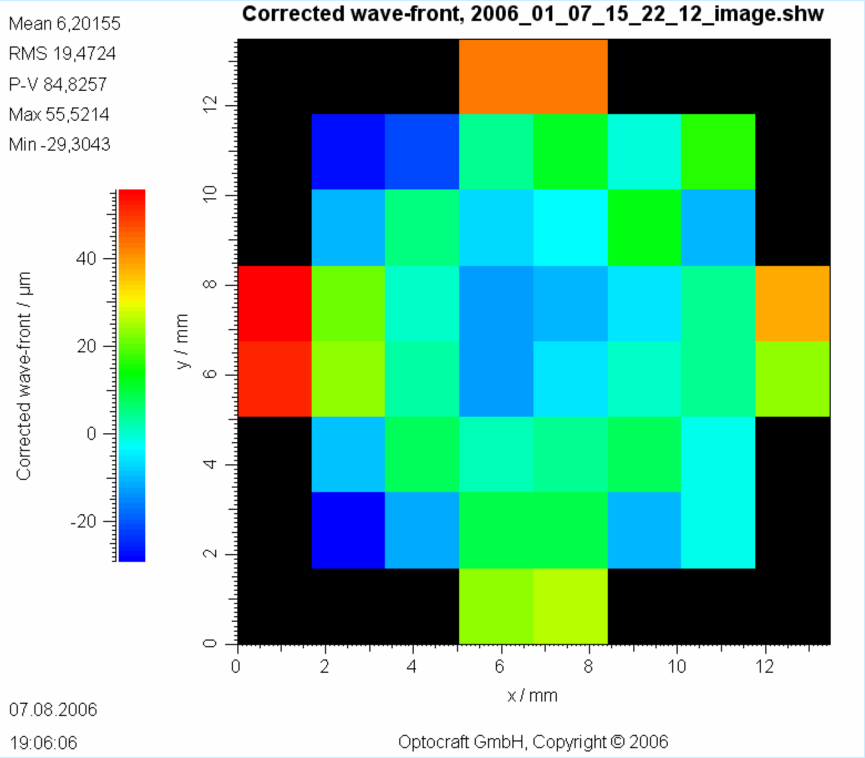


Lateral resolution: LSM

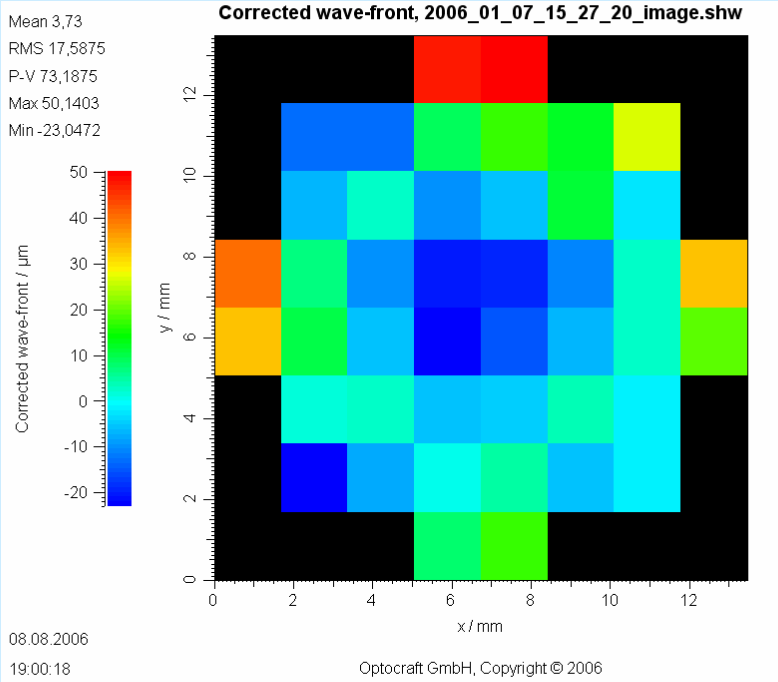
Camera frame

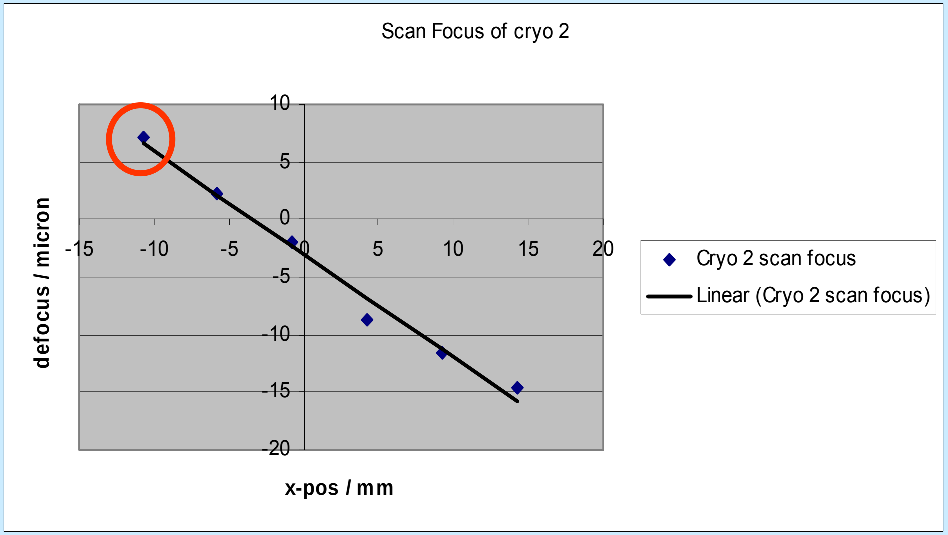


Pure wave-front



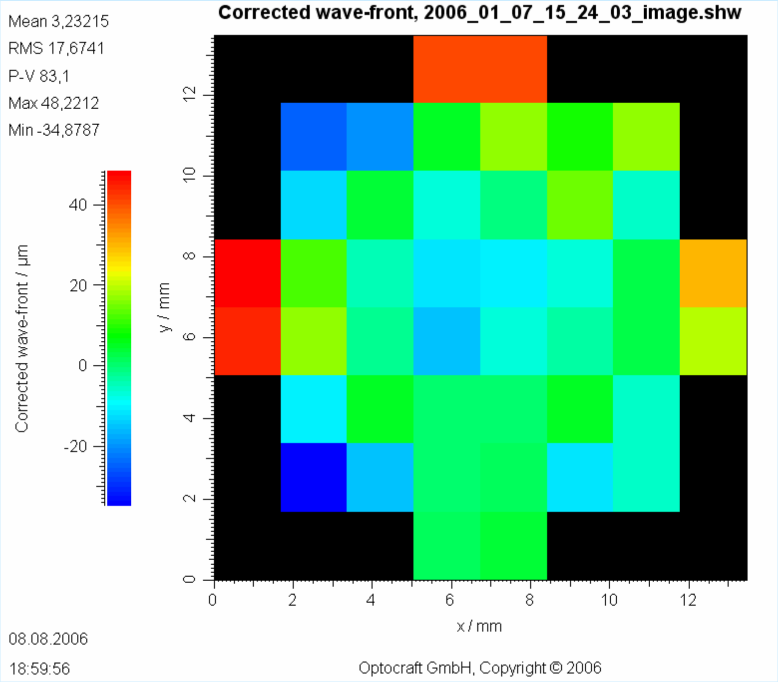
Through Focus scan @ 293K, -10 mm

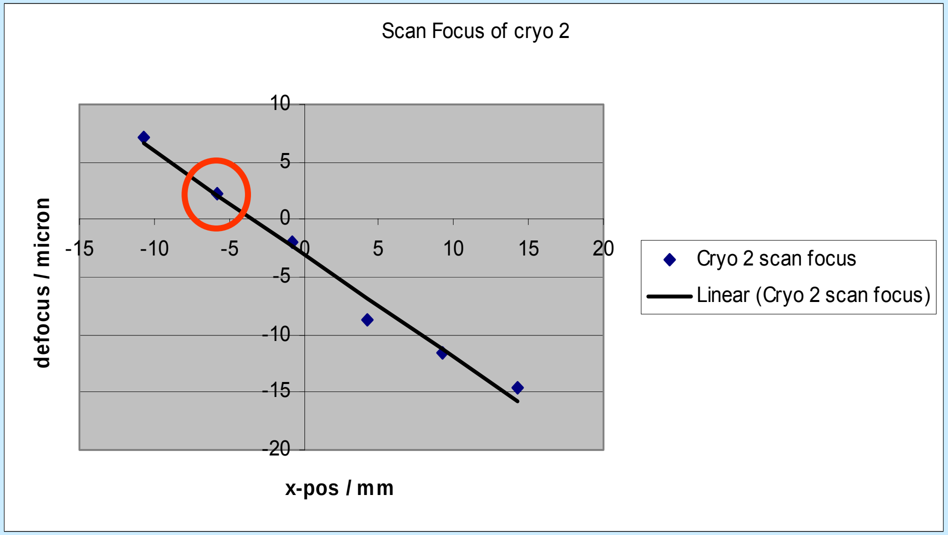




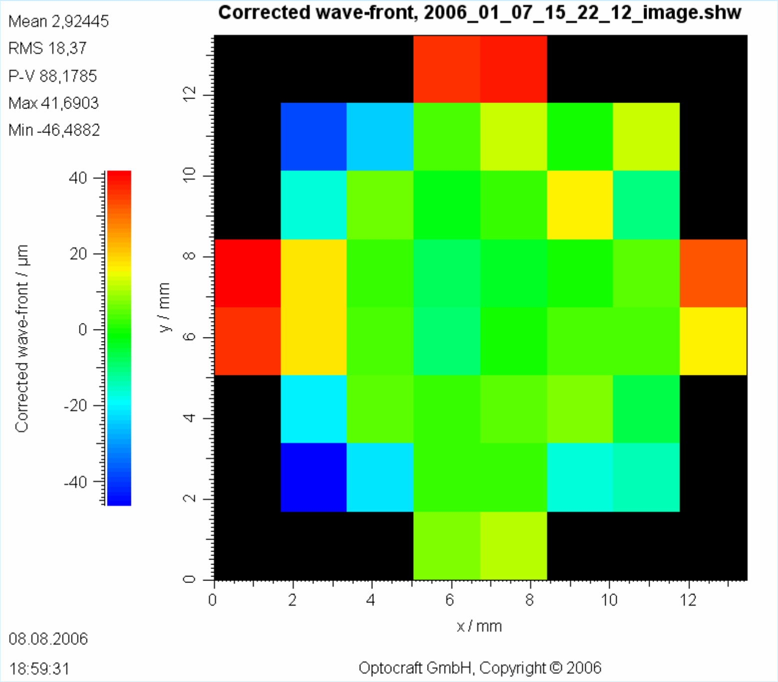
Z4 term vs WFS position

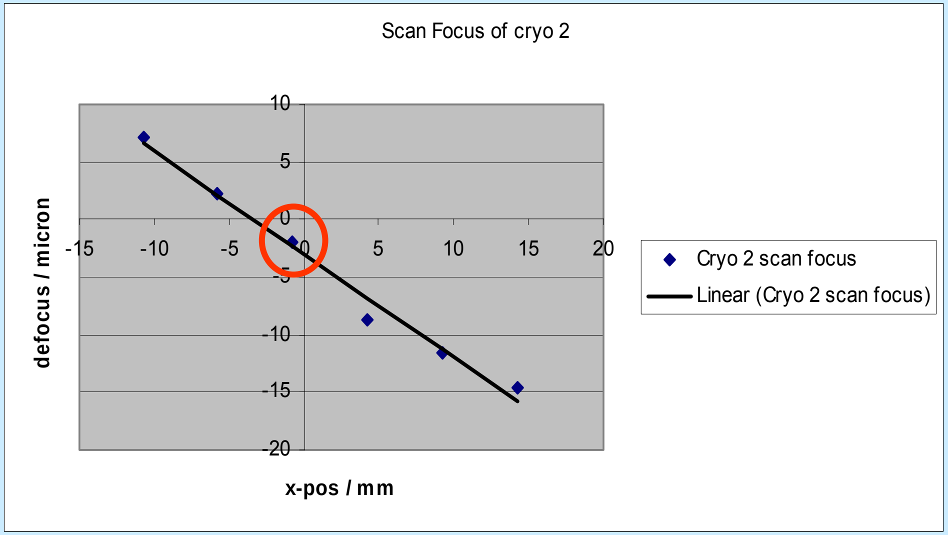
Focus scan @ 293K, -5 mm



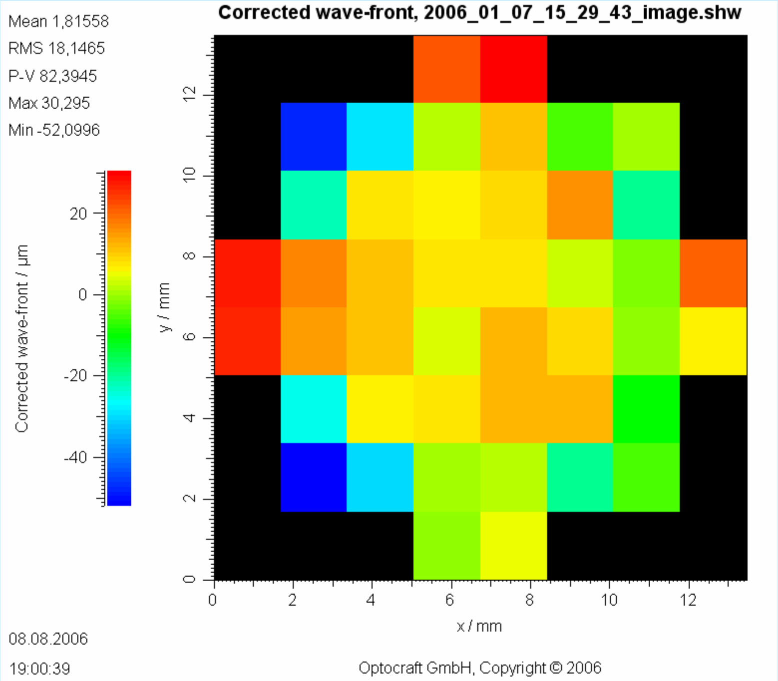


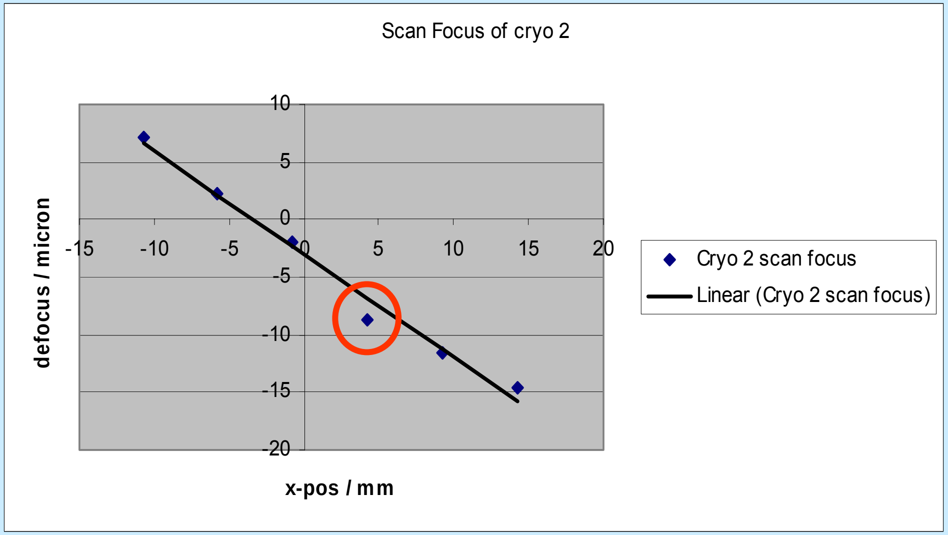
Focus scan @ 293K, 0 mm



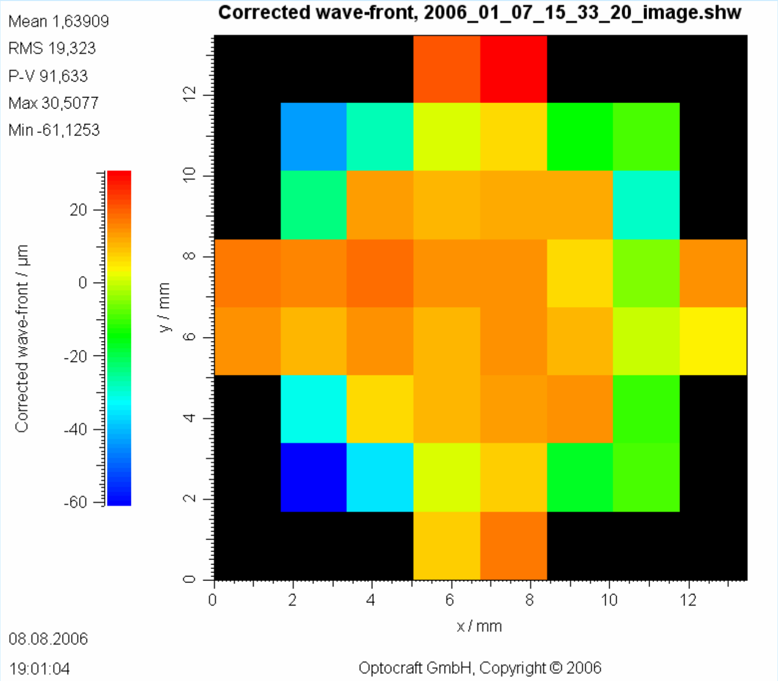


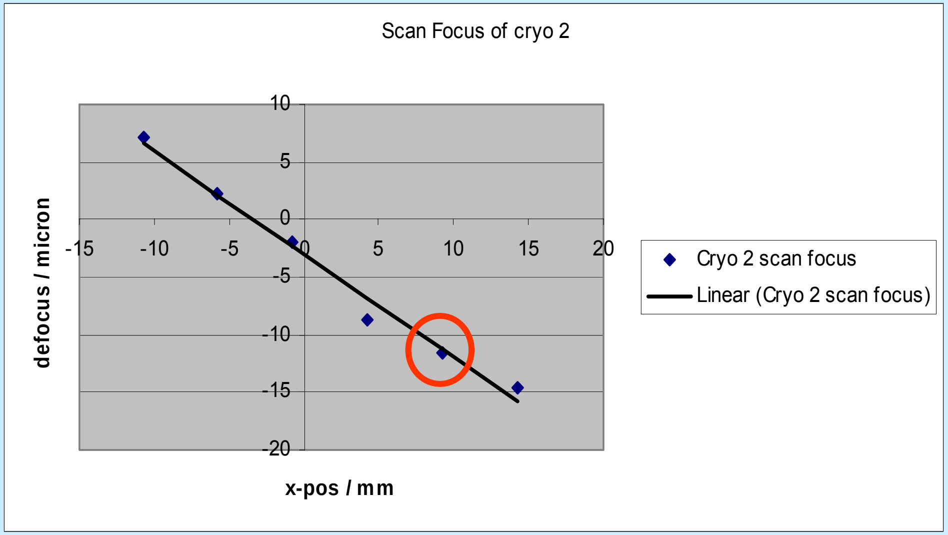
Focus scan @ 293K, +5 mm



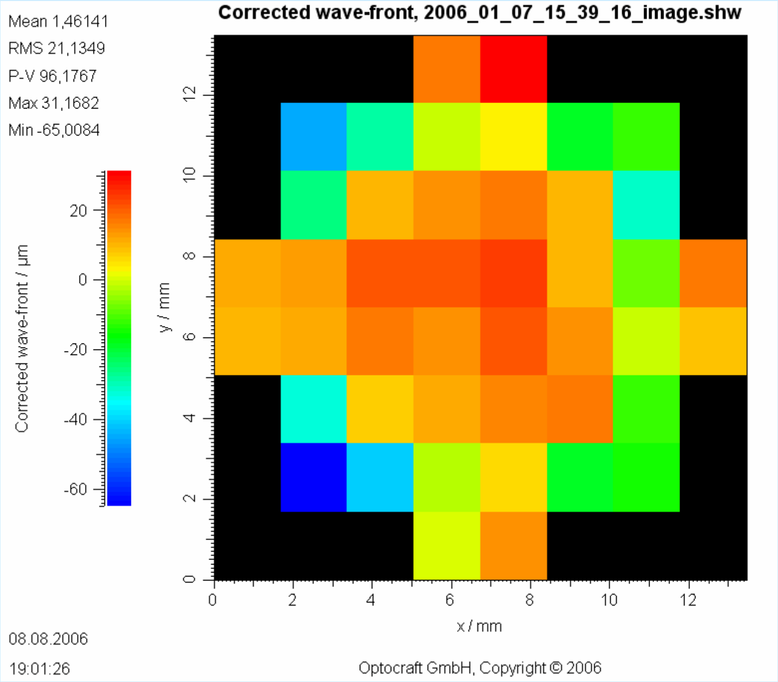


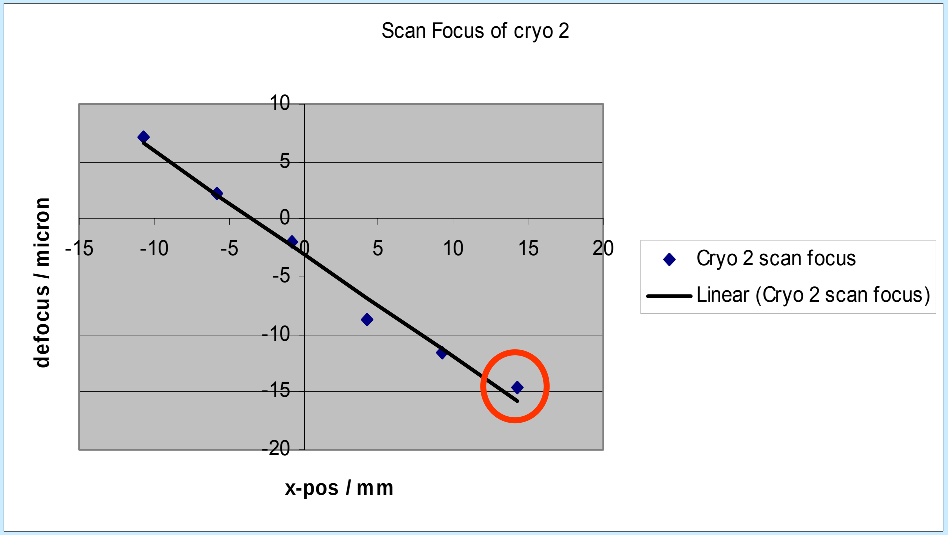
Focus scan @ 293K, +10 mm

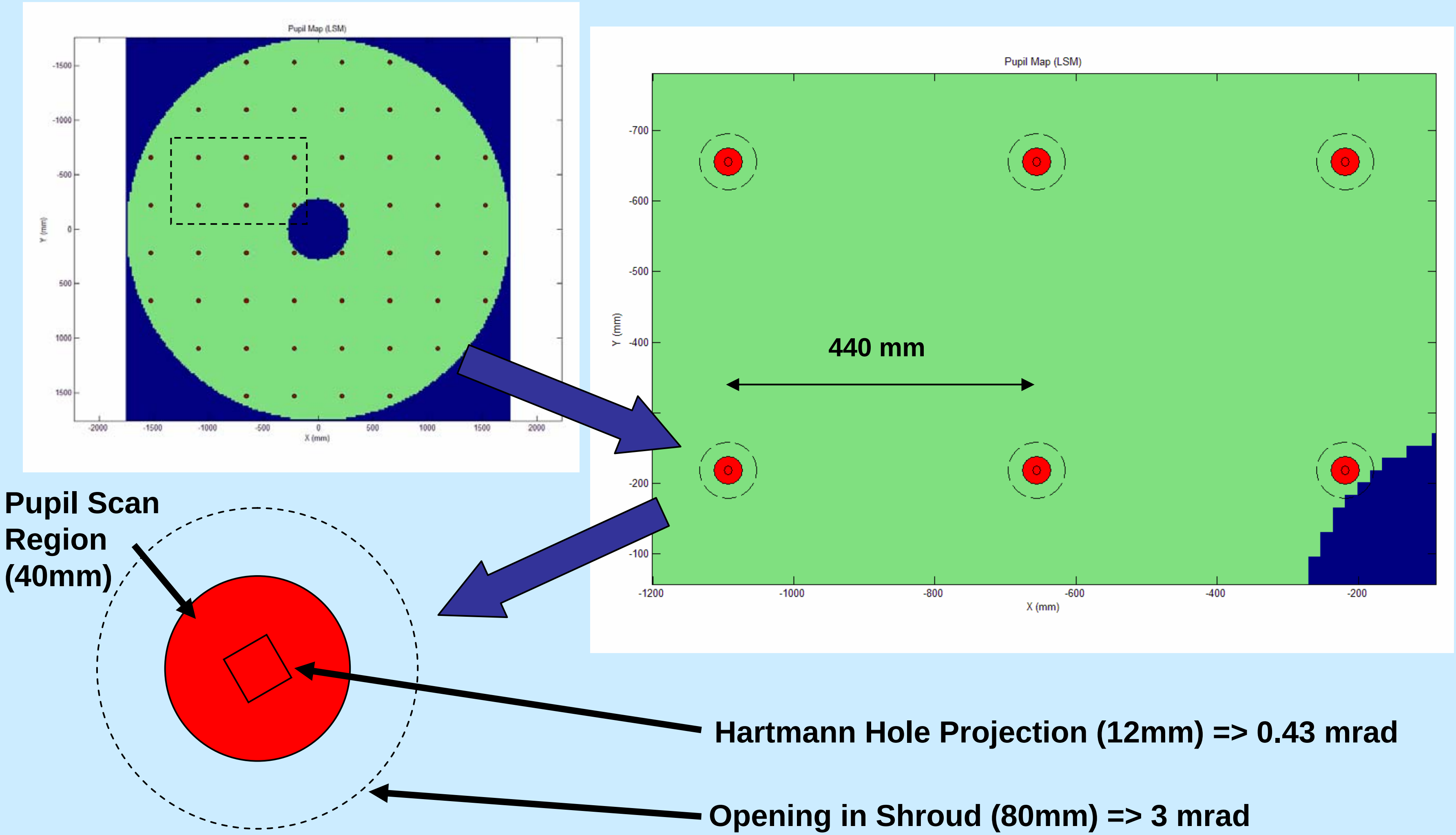




Focus scan @ 293K, +15 mm

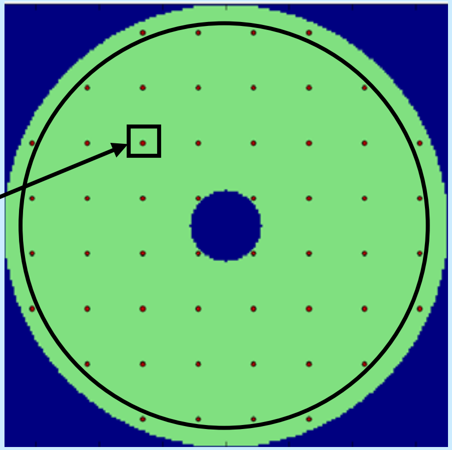




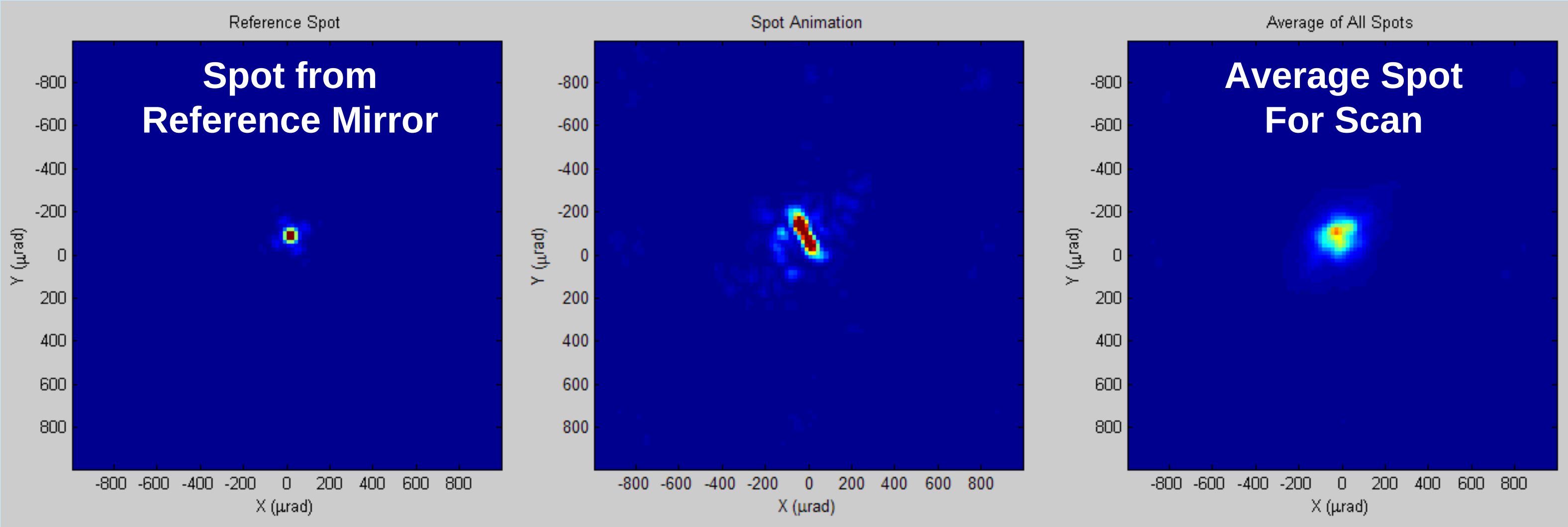

Pupil Map (LSM)
Y (mm)
X (mm)
Pupil Map (LSM)
Y (mm)
X (mm)
440 mm
Pupil Scan Region (40mm)
Hartmann Hole Projection (12mm) => 0.43 mrad
Opening in Shroud (80mm) => 3 mrad

Cryo 2, 70K, Pupil Scan

Spot under Investigation

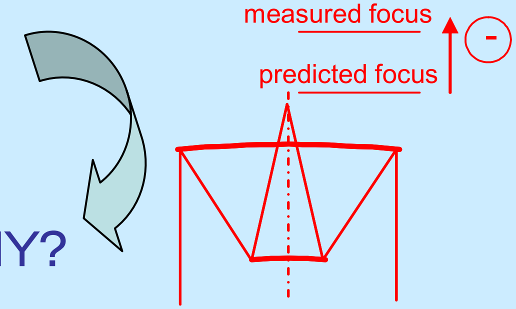


Blurring Of Spot Is Due To Phase Variation Across Hartmann Sample Region

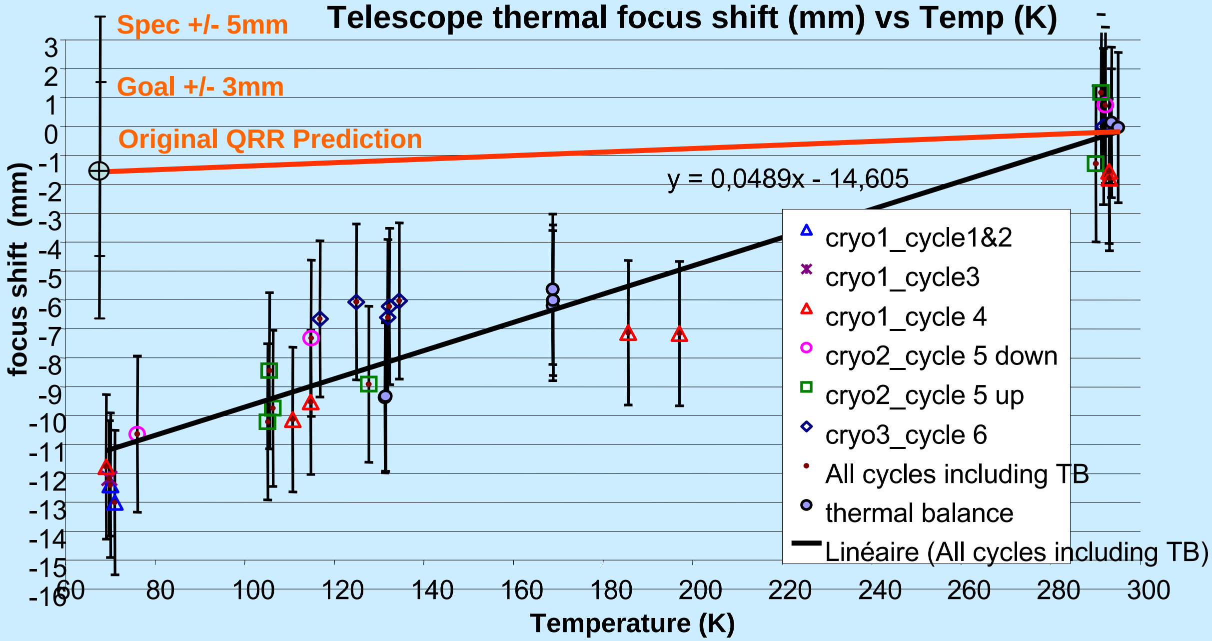


The test results revealed a problem

- Telescope design: Fixed focus & athermal
- As built: Focus moves with temperature – WHY?



Anomaly = discrepancy between the measured focus shift at 70K (-11,7mm) and that predicted (-1.6mm, at QRR)



Spitzer Space Telescope

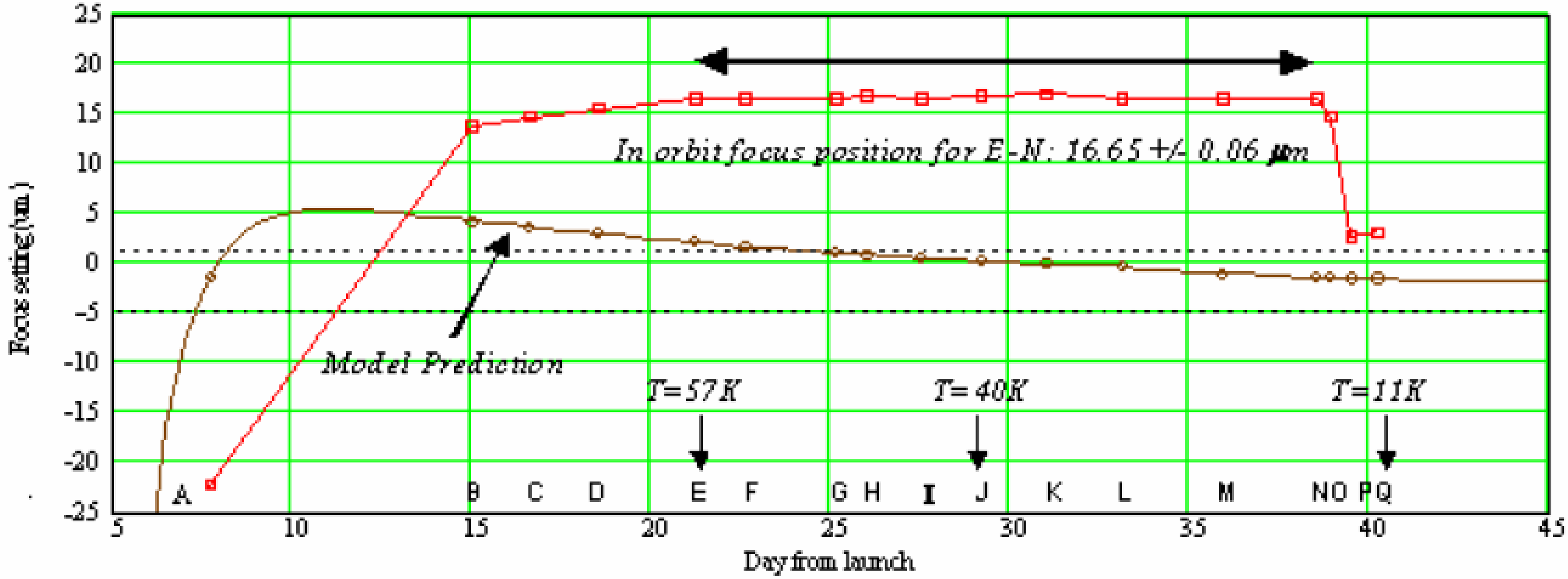


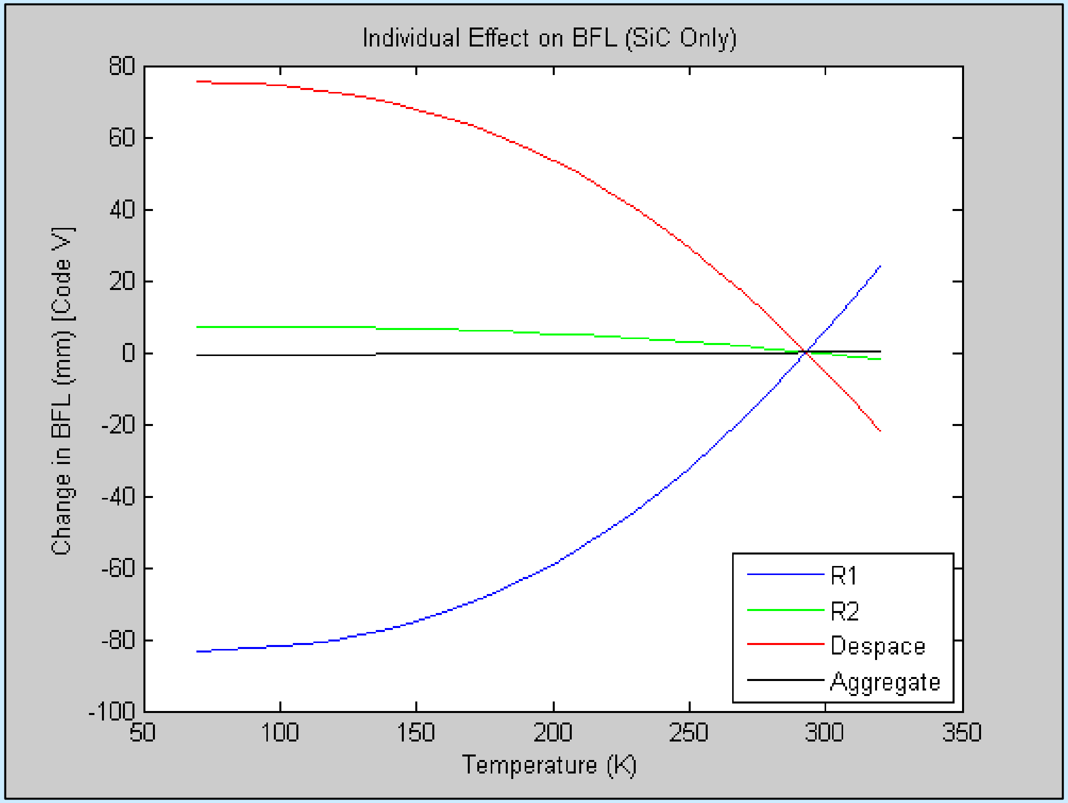
Figure 1. Secondary mirror position versus day from launch. The dashed lines designate the boundaries of the acceptable focus position tolerance band of +/- 3 μm from the target best compromise focus position of -1.8 μm reckoned with respect to our historical hardware and optical model fiducial. Open circles (○) are the predicted IRAC focus position trend calculated with a model that links individual optical, mechanical and thermal models. Square boxes (□) are the IRAC in-orbit focus determination results computed by the Simfit method (Hoffmann et al.[10]). The discrepancy between the actual and model focus positions is most likely due to uncertainties in values for low temperature material properties of the CTA. Telescope focus moves were commanded during the spacecraft uplink and downlink communication events designated with the letters O and P. A third planned focus move was not executed because the image quality requirements stated in the LOR were met after the second focus move.

The state of the focus and image quality of the Spitzer Space Telescope as measured in orbit, Robert D. Gehrz et al Proceedings of SPIE Vol. 5487 (SPIE, Bellingham, WA, 2004)

Why did we have a problem?

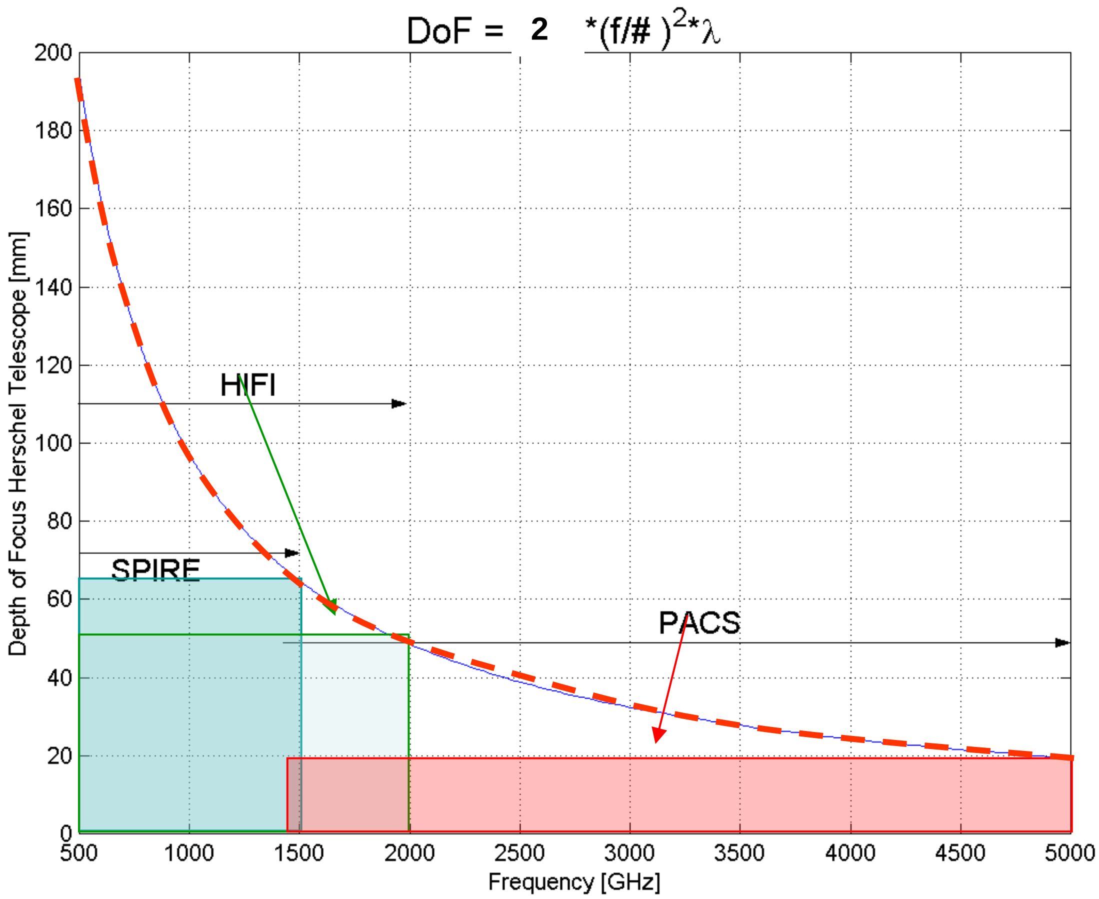
BFL is Difference of Large Numbers

- R1 and Despace
- Despace vs temp is a function of delta CTE between Invar and SiC
- Example with Nominal Material Properties



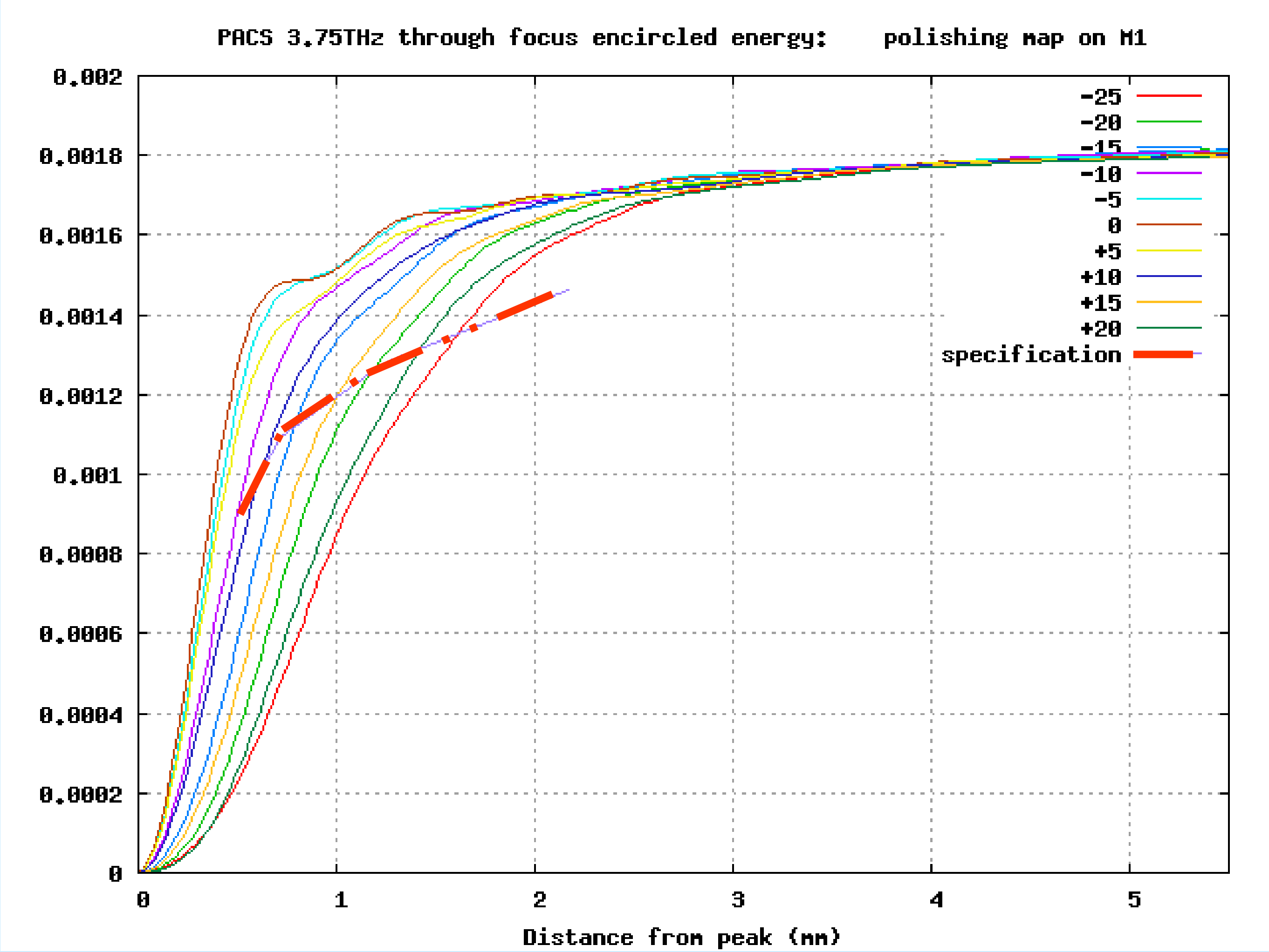
- Materials in the optical cavity of the telescope
  - SiC – CTE values measured 1.03 to 1.52 ppm/K
  - M93 Invar - CTE values 1.35 to 1.93 ppm/K
  - Measurements made over several years in different labs.
  - Choice made for values included in FEM model
  - => Prediction of cold focus based on this model
  - Delta CTE(SiC – M93) 0.1 to 0.7 ppm
- Insufficient CTE measurement accuracy achieved at cryogenic temperatures

Rule of thumb Telescope Full-width Depth of Focus [mm]



- This (Rayleigh criterion) value is used to indicate instrument sensitivity to defocus

- DoF for the shortest specified wavelength (80 micron, 3747 GHz) is ± 12mm



Encircled energy calculated (for as-built telescope) in different planes along the telescope axis. (Using rigorous diffraction theory & RF modeling tool – Grasp-8)

Simulated for instrument line of sight

In spec. in the range –10 to +7 mm

(Reminder theoretical depth of focus ±12 mm.)

In orbit Telescope performances predictions (70K)

reference	Characteristics	Prescription	Goal	Obtained
TEPE-050	WFE	6 μm rms	-	5.5 μm rms at nominal focus, at FOV edge
	Encircled energy	80% in r=2.1 mm		80% in r=1.4 mm
TEPE-150	Back focus	Min 795 mm Max 805 mm	797 mm 803 mm	800.0 mm with +15.7 mm IF shims thickness
TEPE-155	Knowledge tolerance	± 3 mm	± 2 mm	± 3 mm ptv
TEPE-150	Focus decenter	< 5 mm	< 3 mm	- 0.1 mm Y axis +0.5 mm Z axis
TEPE-155	Knowledge tolerance	± 3.5 mm	± 2 mm	± 3.1 mm ptv
TEPE-160	Pupil decenter	< 3 mm	< 2 mm	-0.4 mm Y axis +0.2 mm Z axis
	Knowledge tolerance	± - 1 mm	± 0.5 mm	± 0.5 mm ptv
TEFU-007	Line of Sight bias	< 3 mrd	-	< 0,2 mrd
	Knowledge tolerance	± 2 mrd		
TEPE-065	Focal length	Min 28650 mm Max 28350 mm	-	28623 mm
	Knowledge tolerance	± 90 mm		± 76 mm
	f-number	Min 8.68 Max 8.70	-	8.70

- Herschel telescope performance achieved

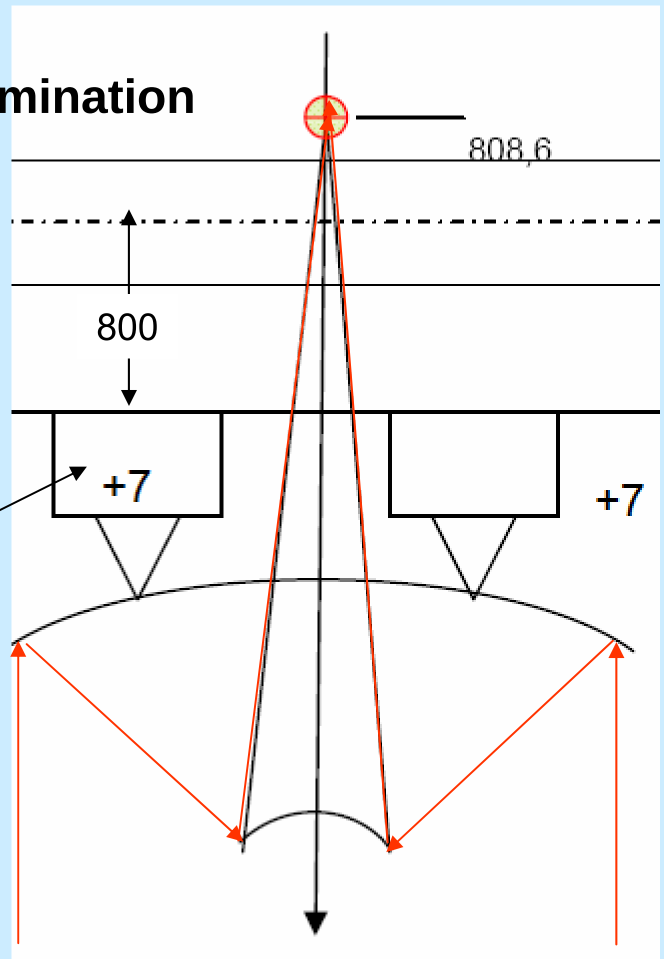
Herschel Focus Shimming

ASEF Cryo. determination

Focus position (spec + range)

CVV Interface

Nominal Shim



(Ref. RFW 1035)

± 3.03 mm uncertainty

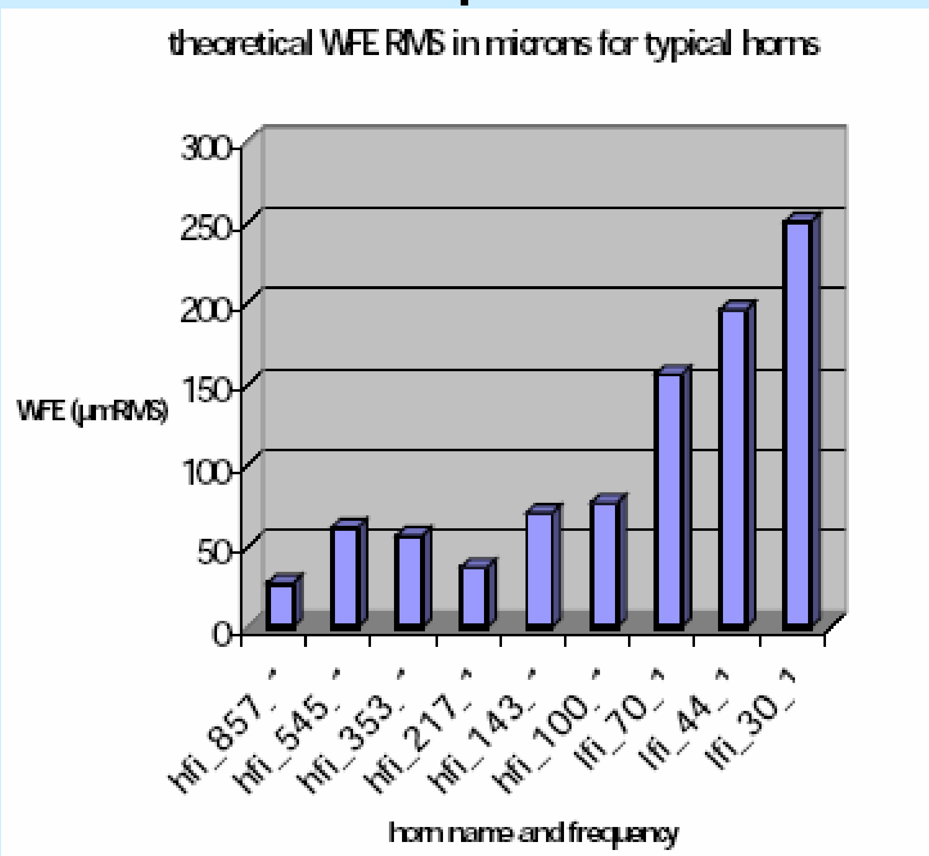
Tiger Team Assessment
- Metrology OK
- FEM OK
- Material CTE knowledge accuracy Not OK
- Instrument sensitivity to defocus – Not Critical – but no risks to be taken.

Solution:
Add 8.6 mm shim to bring focus back to nominal specified position

- Planck telescope technology
  - Carbon Fibre Reinforced Plastic (CFRP) material was chosen for both reflectors and structure
  - Available in Europe
  - Mature, space qualified and well understood
  - Lightweight & Stiff
  - Heritage in other sub-mm telescopes, ADMIRALS, ODIN
  - However cryogenic verification remained a challenge!

- Planck telescope performance
  - Unusual approach taken for specification of WFE due to discreet and dispersed nature of detectors (horns) in focal “plane”
  - For each horn its “phase centre” is placed on the focal surface and
  - Its pointing direction is aligned with the chief ray of the telescope at that field position
  - For each horn a specific WFE value (and gain degradation) is calculated
  - Finally, an apodization factor is also taken into account for each horn

- WFE representation



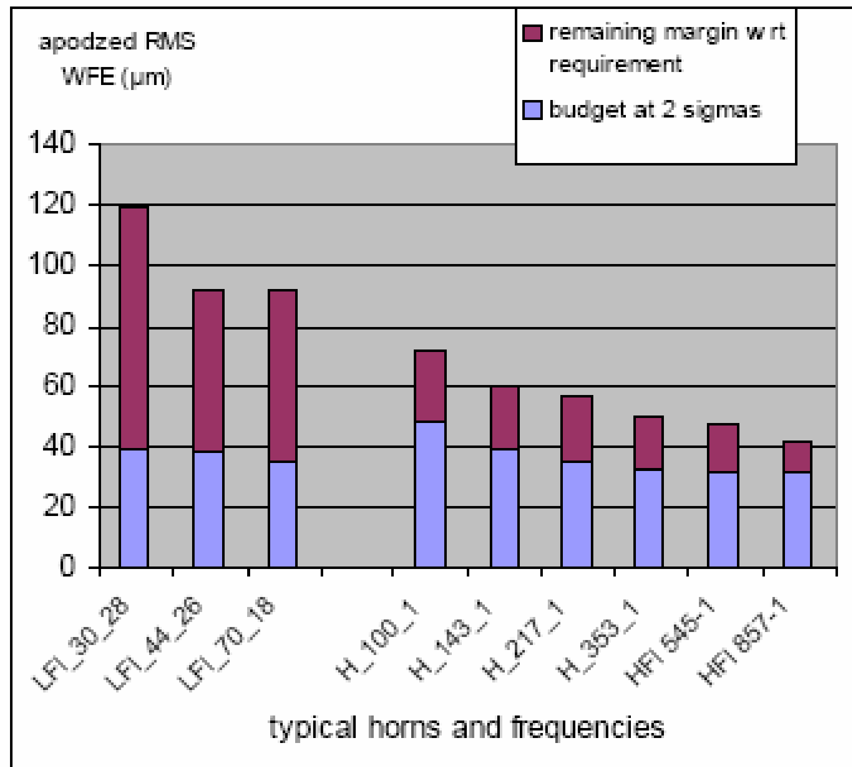
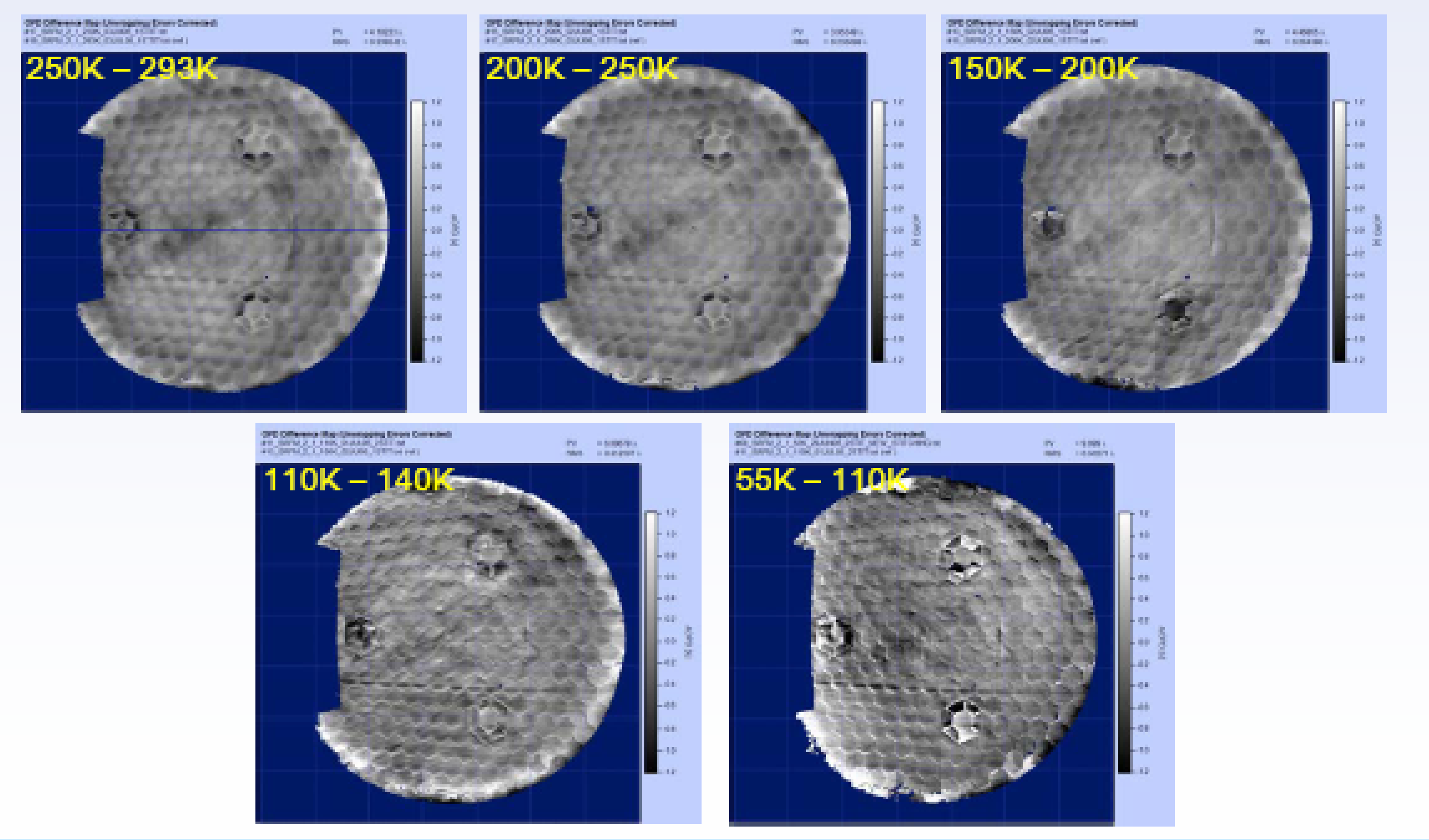


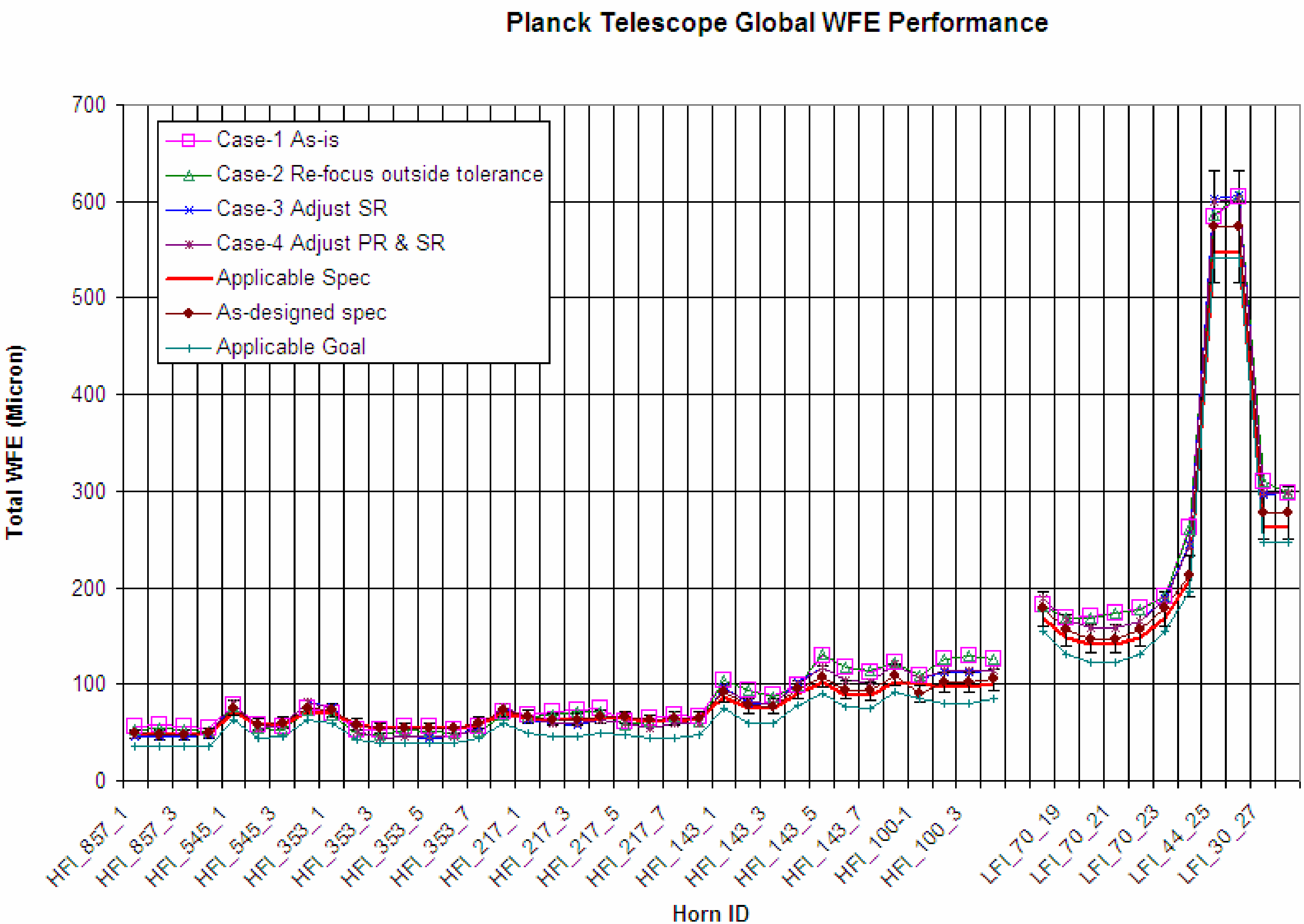
Fig. 15: Wavefront error degradation budget

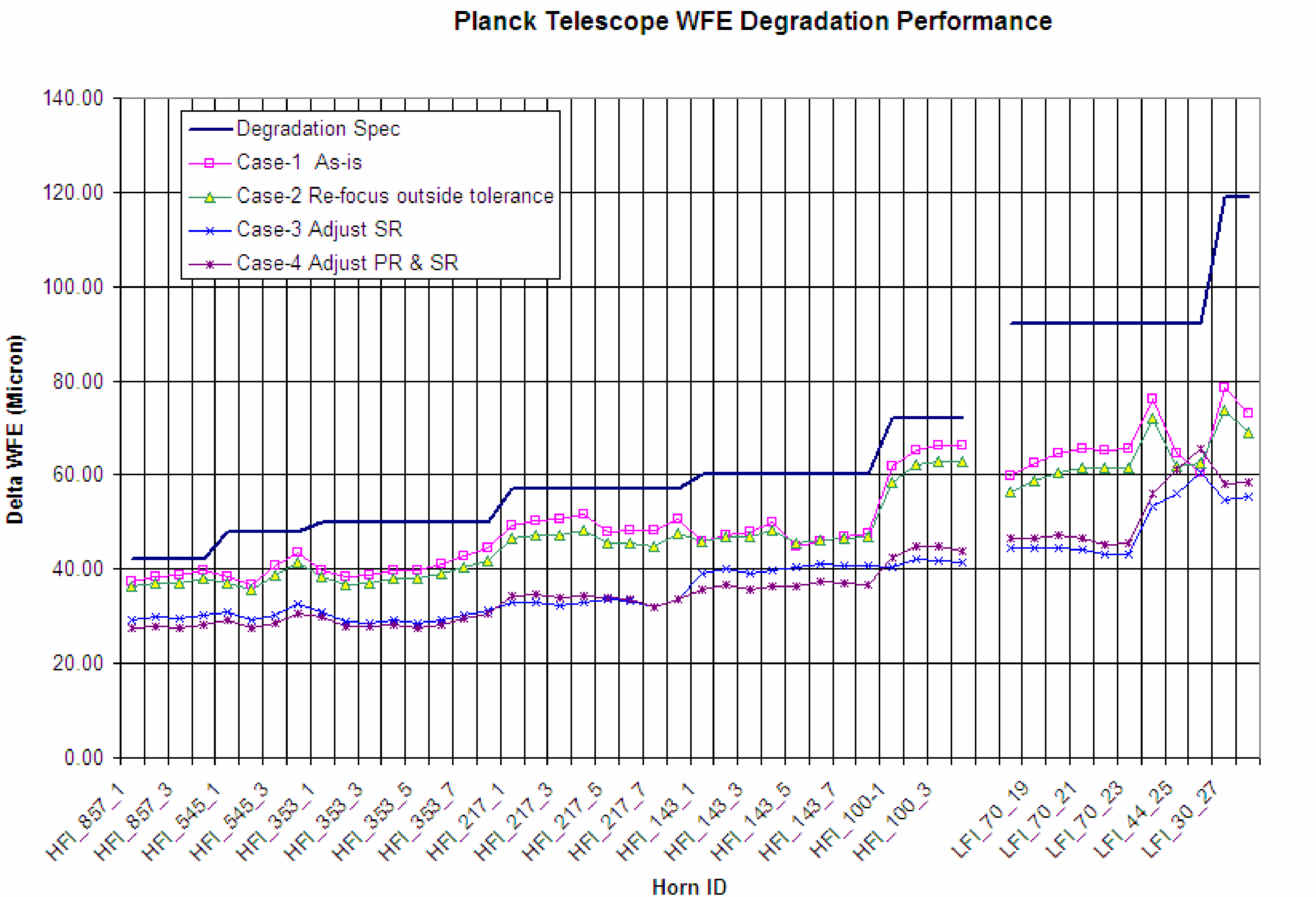
- Planck telescope test metrology
  - Planned was a combination of
    - Reflector surface interferometry (for high spatial resolution SFE)
    - Sequential or scanning Hartmann at Telescope level under cryo vacuum
    - 3d mechanical measurements of structure and alignment fixtures at ambient
  - Realised was
    - 3d ambient measurements
    - Cryo interferometry of reflectors – but SR only giving useful data
    - Videogrammetry of PR, SR and entire telescope under cryo conditions

• Reflector interferometry

– 10.6 micron interferometer developed for purpose at CSL (B)
– Local large slopes due to honeycomb print-through (quilting) proved to be a limiting factor giving unwrapping errors




Planck Telescope Global WFE Performance
Case-1 As-is
Case-2 Re-focus outside tolerance
Case-3 Adjust SR
Case-4 Adjust PR & SR
Applicable Spec
As-designed spec
Applicable Goal
Total WFE (Micron)
700
600
500
400
300
200
100
0
HFI_857_1
HFI_857_3
HFI_545_1
HFI_545_3
HFI_353_1
HFI_353_3
HFI_353_5
HFI_353_7
HFI_217_1
HFI_217_3
HFI_217_5
HFI_217_7
HFI_143_1
HFI_143_3
HFI_143_5
HFI_143_7
HFI_100-1
HFI_100_3
LFI_70_19
LFI_70_21
LFI_70_23
LFI_44_25
LFI_30_27
Horn ID


Planck Telescope WFE Degradation Performance
Degradation Spec
Case-1 As-is
Case-2 Re-focus outside tolerance
Case-3 Adjust SR
Case-4 Adjust PR & SR
Delta WFE (Micron)
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
HFI_857_1
HFI_857_3
HFI_545_1
HFI_545_3
HFI_353_1
HFI_353_3
HFI_353_5
HFI_353_7
HFI_217_1
HFI_217_3
HFI_217_5
HFI_217_7
HFI_143_1
HFI_143_3
HFI_143_5
HFI_143_7
HFI_100-1
HFI_100_3
LFI_70_19
LFI_70_21
LFI_70_23
LFI_44_25
LFI_30_27
Horn ID

- Herschel Telescope lessons learned
  - At cryogenic temperatures accurate knowledge of material properties is critical
  - Testing optical performance of large telescopes under cryogenic vacuum conditions is NOT easy => always leave margins for unexpected problems
  - Always use different tools (and independent experts) for analysis of difficult problems; complementarities & cross-verification can be vital
  - Single contractor approach very good

- Planck Telescope lessons learned
  - CFRP remains a challenging material system for high performance optical reflectors (mirrors), especially at cryogenic temperatures
  - Writing meaningful and clear specifications for telescope performance in the sub-mm is not easy – could have been done better (optical & RF engineers think differently!)
  - High (spatial) resolution surface form error metrology of large reflectors remains a significant challenge under cryogenic vacuum conditions
  - End to end telescope performance testing of Planck (at operational temperatures) proved to be unfeasible => a new approach needs to be determined for next sub-mm system
  - Multiple contractor procurement strategy was a significant disadvantage

- Future ESA space telescope challenges
  - GAIA
  - JWST
  - LISA
  - DARWIN
  - Cosmic Vision …..?

- Acknowledgements
  - Herschel Planck team at ESTEC
  - Herschel Telescope Tiger Team (BB especially!)
  - EADS Astrium (Toulouse)
  - Alcatel Alenia Space (Cannes)

  - SSOM for the opportunity
  - You for your attention (& patience)!
  - Have a safe trip home

- Backup slides

Planck Telescope "Depth of Focus" Spec

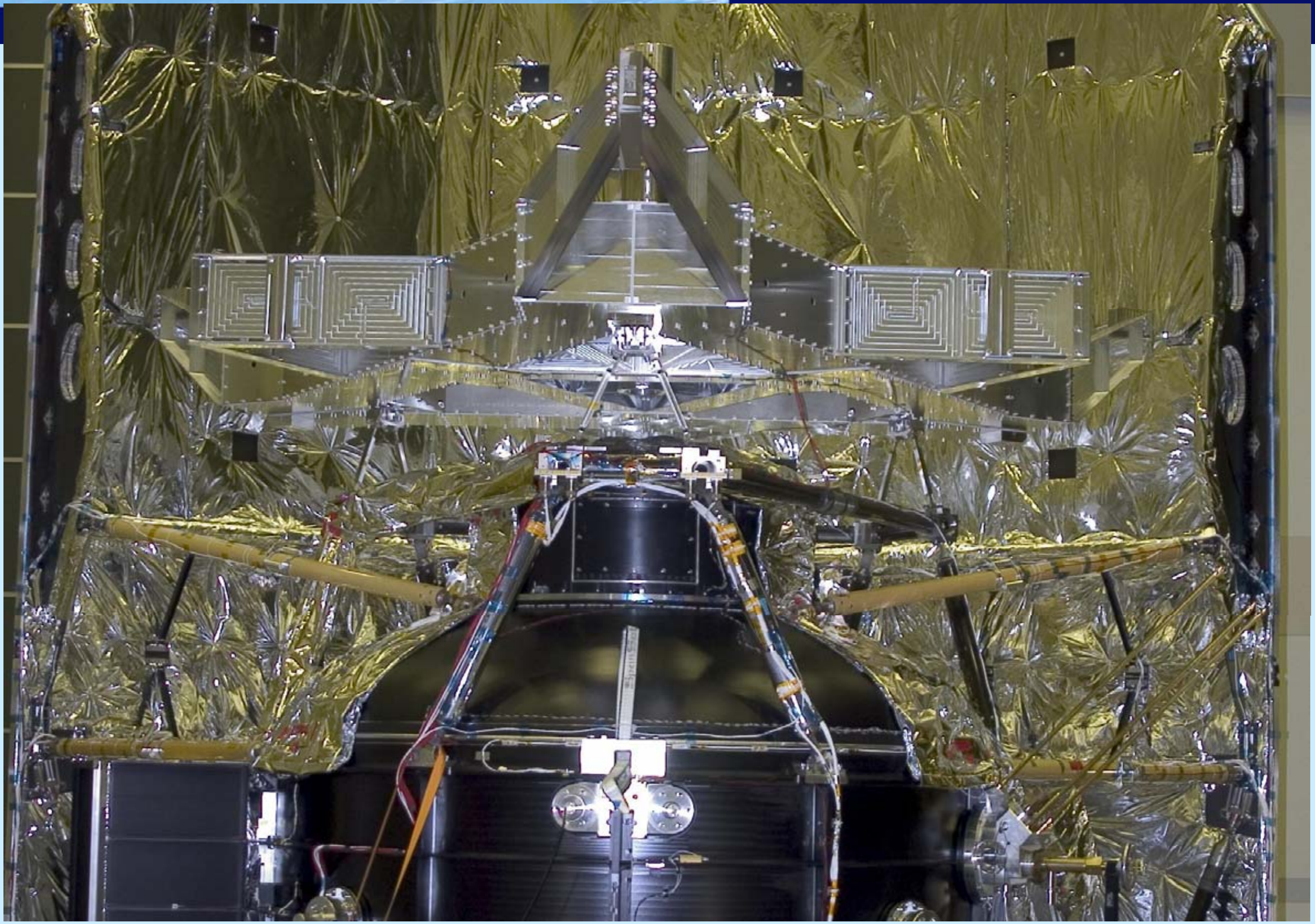
5.3.3 ALIGNMENT

In this specification a requirement is placed only on the internal telescope alignment, i.e. the alignment of the FPU to the telescope is not covered, since not under the responsibility of the telescope.

PTPE-085 *The nominal focus of the telescope shall be within a cylinder of diameter of 1 mm (tbc) and length of 1 mm (tbc) around the theoretical nominal focus position, with the cylinder axis in the Z_{FPU} direction of the FPU coordinate system.*

PTPE-090 *The nominal focus of the telescope shall be known to be within a cylinder of diameter of 0.6 mm (tbc) and length of 0.5 mm (tbc) around the theoretical nominal focus position, with the cylinder axis in the Z_{FPU} direction of the FPU coordinate system.*

- ESA SCI-PT-RS-07024 Iss. 1, P 21



TMS

Detail

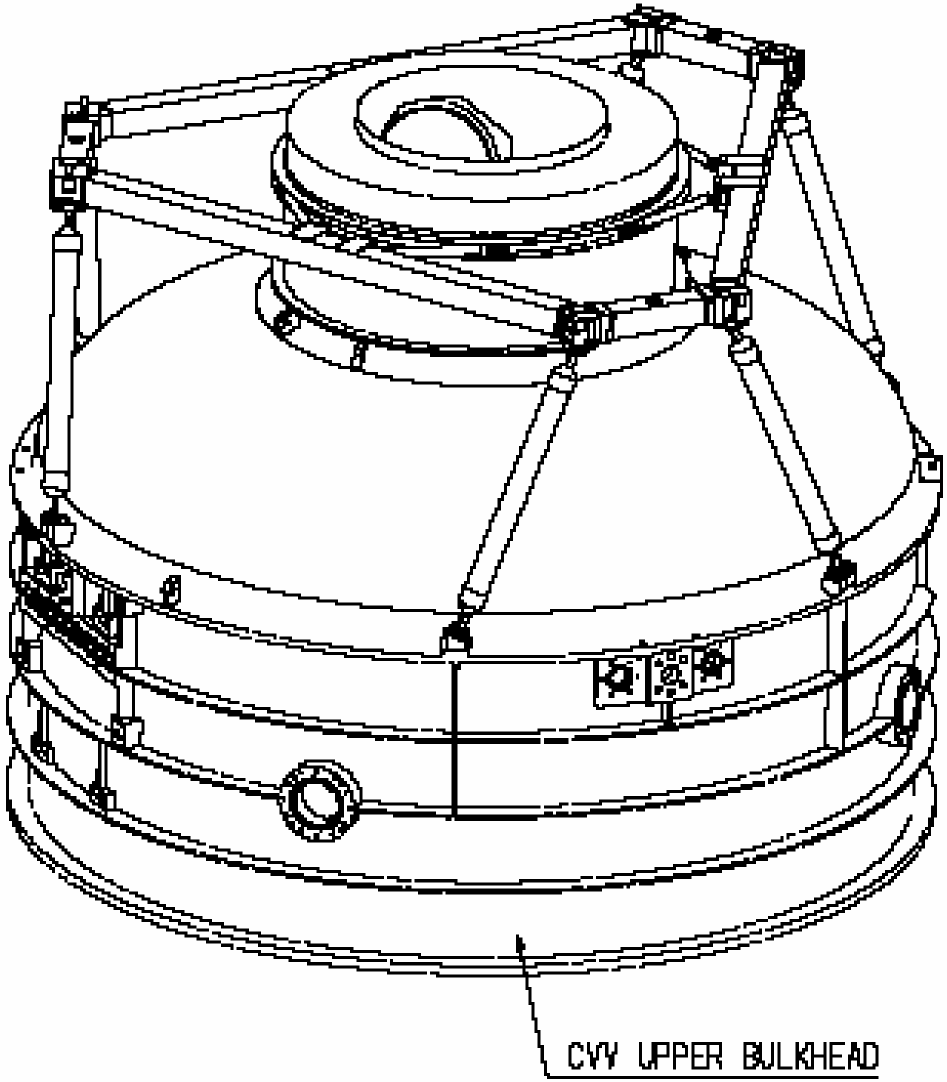
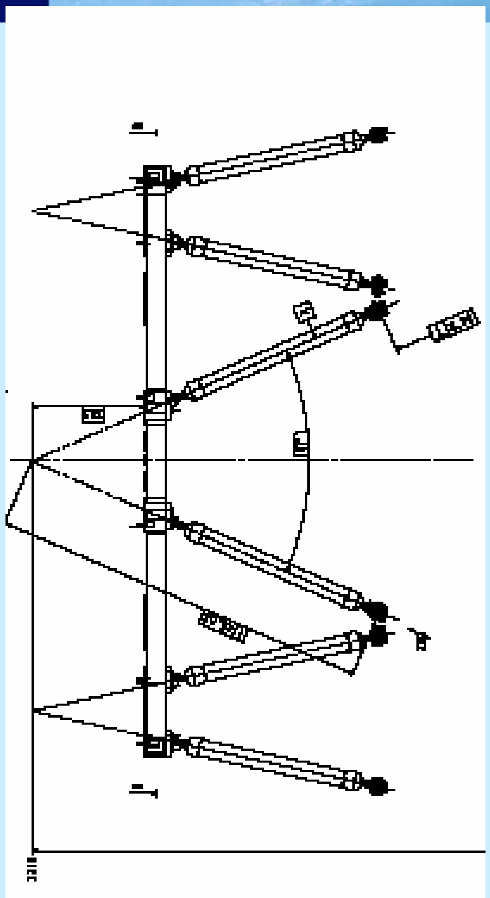
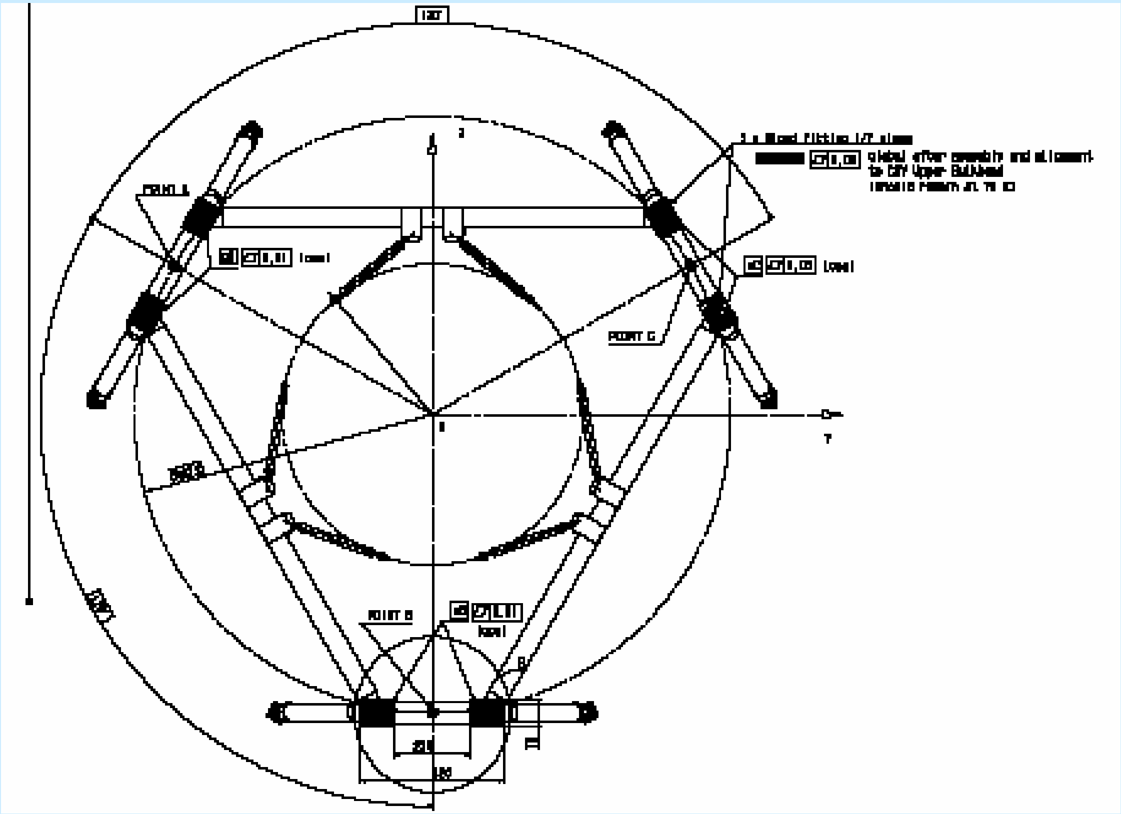


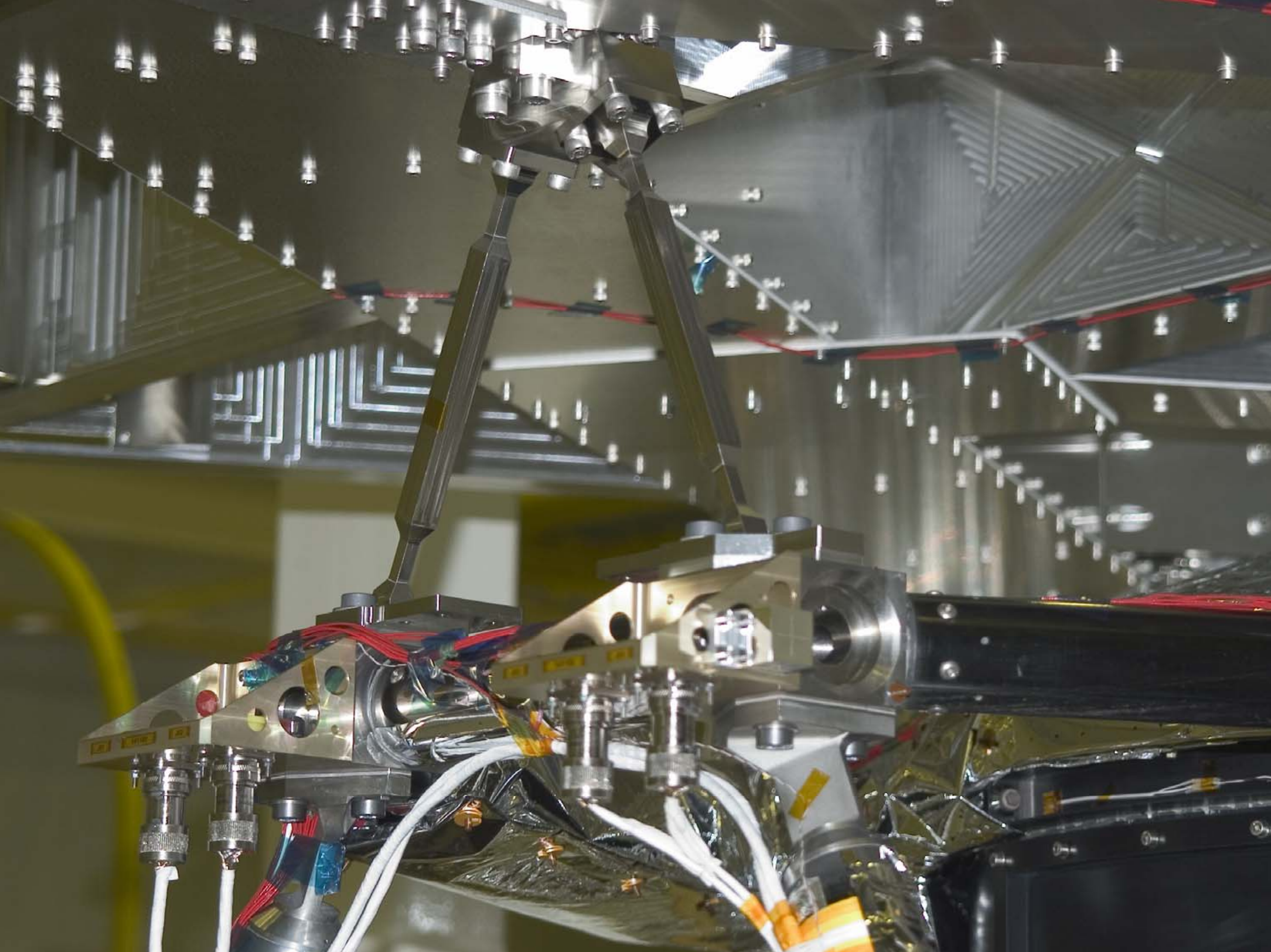
Figure 23: Herschel Telescope CVV fixation structure mounted onto CVV.

The CVV struts are designed such that a radial shrinkage of the CVV of 4 mm is possible without distorting the interface frame and its interface to the telescope.
To avoid distortion of the telescope, the interface frame has to guarantee an interface planarity of 80 µm.
The upper frame TMS allows radial shrinkage of the CVV interface and limits the distortion effects to the telescope.





Telescope Mounting Structure (TMS)



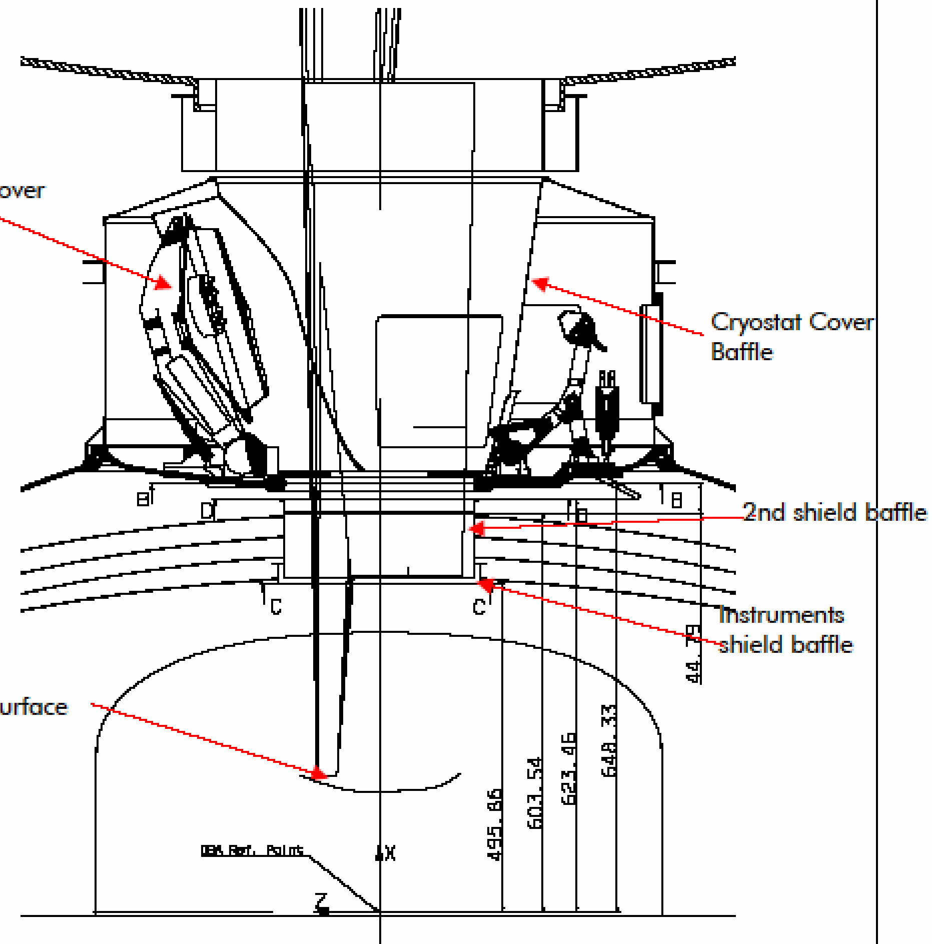


Figure 4.3-8: Overall configuration of beam entrance