MT MECHATRONICS

Flexible Body Control of Large Telescope Structures

LMT/GTM

HWFE Requirement 75 µm rms
Pointing Requirement 1.0 arcsec rms
(at 10m/s operational wind speed)

SOFIA

Pointing Requirement
0.4 arcsec rms

DKIST

Jitter Requirement
0.075 arcsec rms

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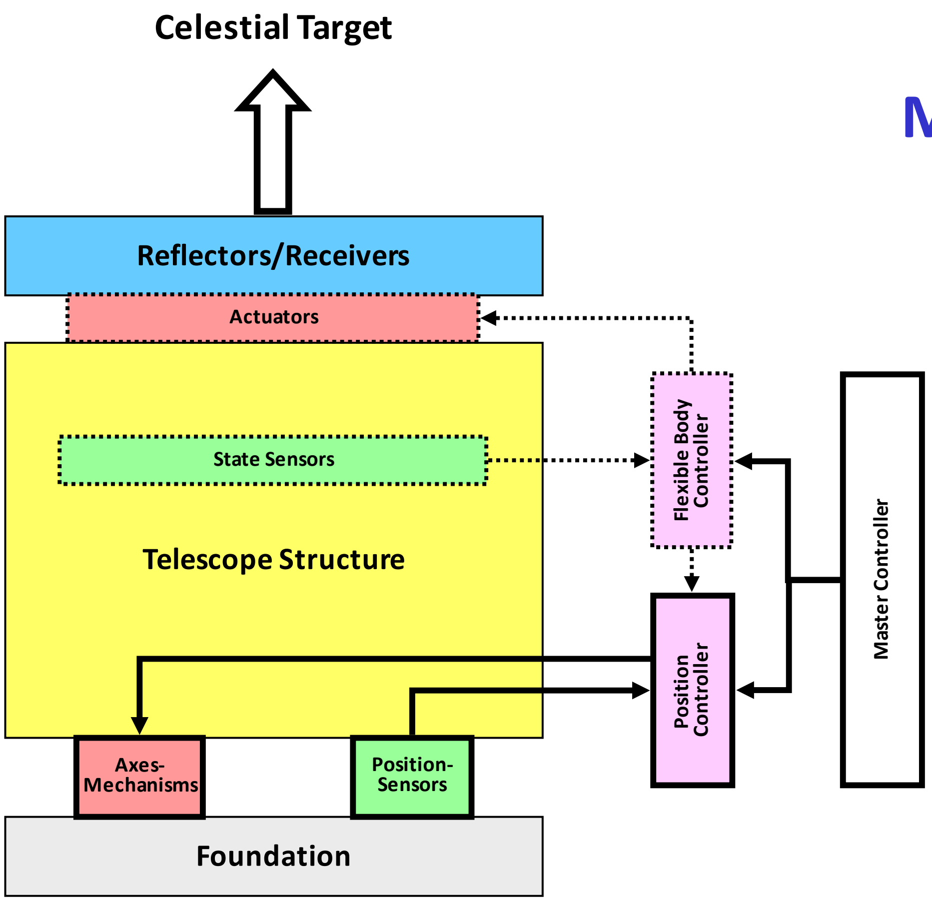
Flexible Body Control of Large Telescope Structures



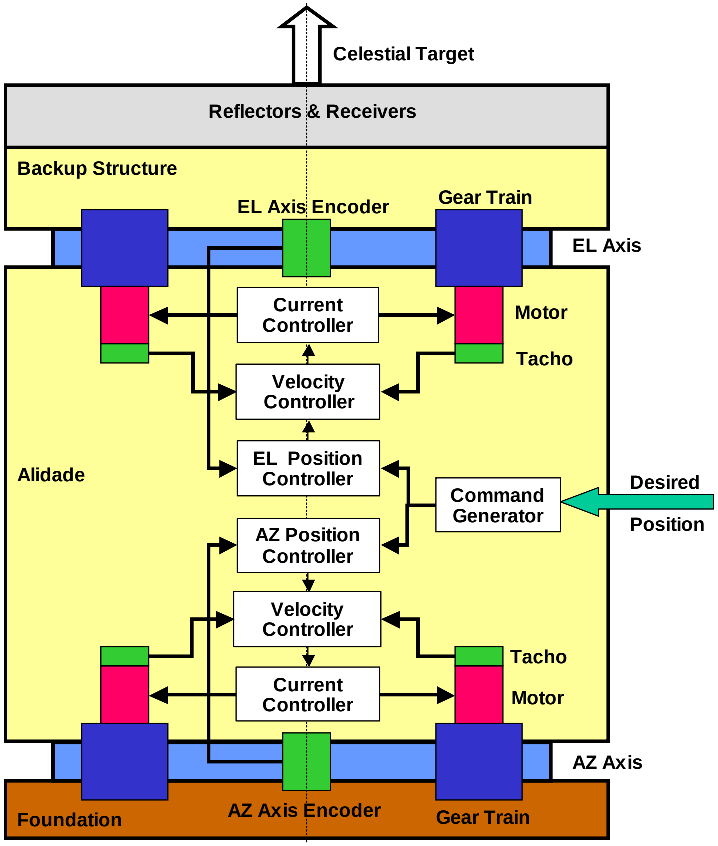
Mechatronic Point of View!

Relying not only on “Metrology alone” but adding “Structural Intelligence” to the control architecture

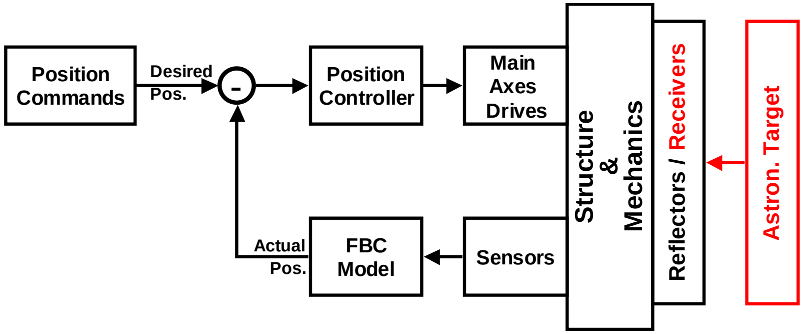
H. J. Kärcher, “Telescopes as Mechatronic Systems”, *IEEE Antennas and Propagation Magazine*, vol.47, 2005

Position Control vs. Flexible Body Control

Standard cascaded main axes control architecture



Basic FBC control architecture



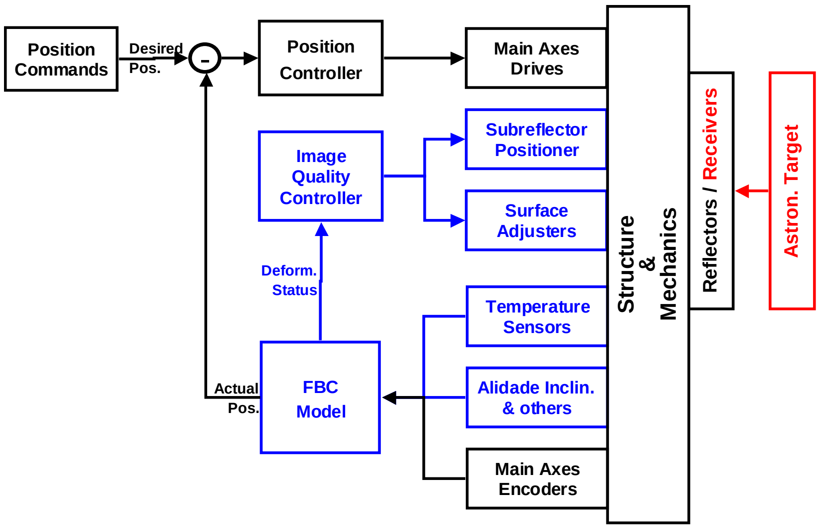
FBC sensing alternatives:

I. Existing information of the classical main axes control system
II. External metrology
III. State sensors on the structure
IV. Imaging sensors in the focal plane

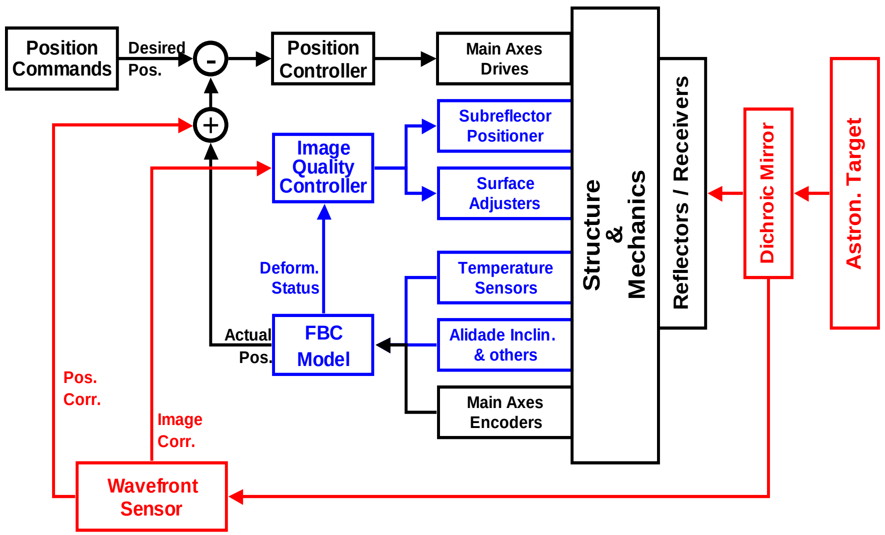
H. J. Kärcher, "Telescopes as Mechatronic Systems", *IEEE Antennas and Propagation Magazine*, vol.47, 2005

Flexible Body Control vs. Adaptive Optics

Flexible Body Control (FBC)



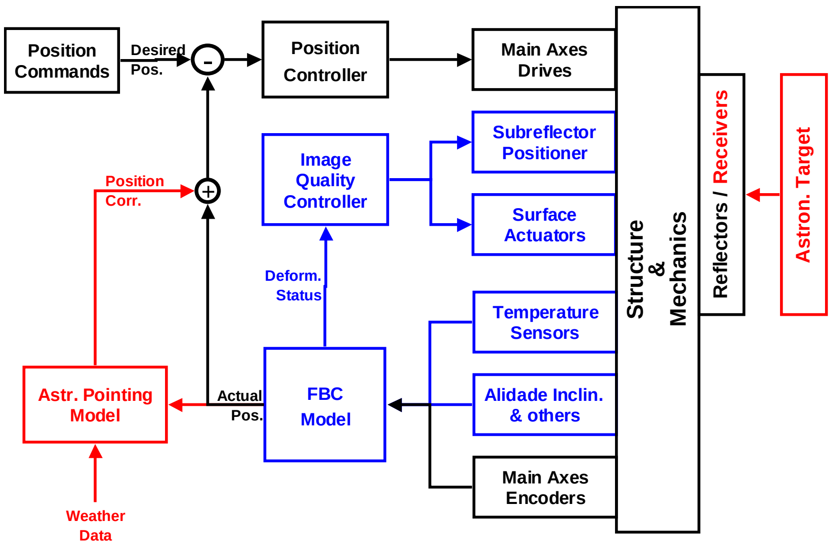
Adaptive Optics (AO)



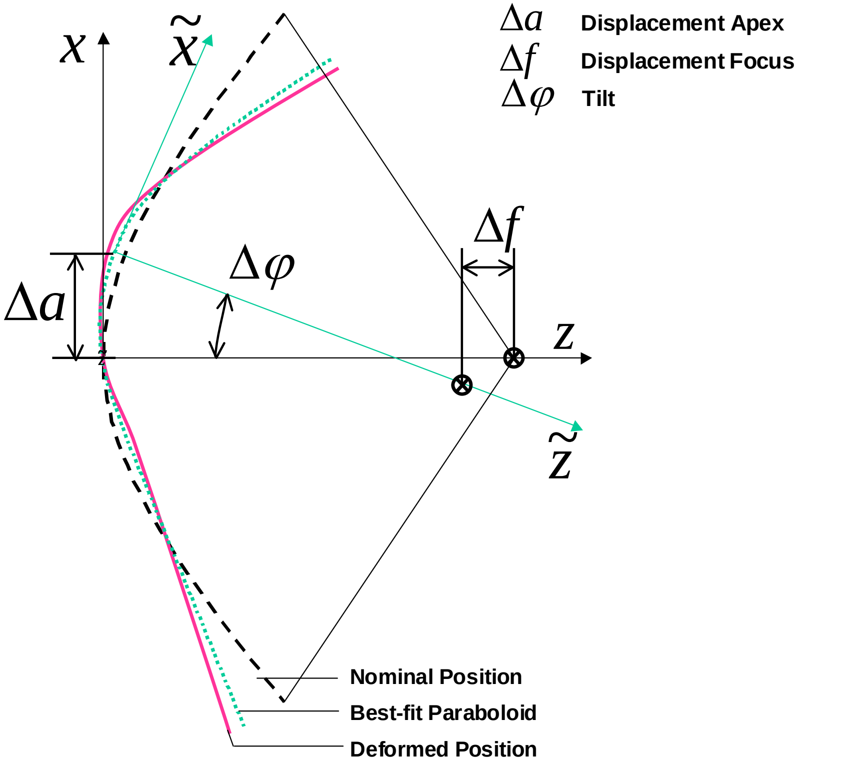
H. J. Kärcher, "Telescopes as Mechatronic Systems"
IEEE Antennas and Propagation Magazine, vol.47, 2005

Astronomical Pointing Calibration & Related Optics

Astronomical Pointing Model



Best-fitting Algorithm – Ray Tracing



H. J. Kärcher, "Telescopes as Mechatronic Systems"
IEEE Antennas and Propagation Magazine, vol.47, 2005

Deformation

Sensing

Overview

	Sensor Type	Kind of Information	Main Application
a	angular encoders	relative angular position of adjacent structural components	position control of earth based telescopes
b	tachos	motor velocities	
c	current sensors	motor torques	
d	inclinometers	inclination of attachment flange against local gravity	FBC for radio telescopes
e	laser trackers	relative spatial position of target points	
f	temperature sensors	absolute temperature	
g	pressure sensors	aerodynamic pressure at attachment area	
h	strain gauges	strain at attachment area	
i	imagers	position of a reference target	position control and FBC for airborne (and space) telescopes
j	gyros copes	angular velocities	
k	accelerometers	lateral accelerations	
l	wave front sensors	image and position of a reference target in the focal plane	adaptive optics
m	weather stations	wind speed, wind direction, outside temperature etc.	general

Deformation Sensing II

Examples of Sensors

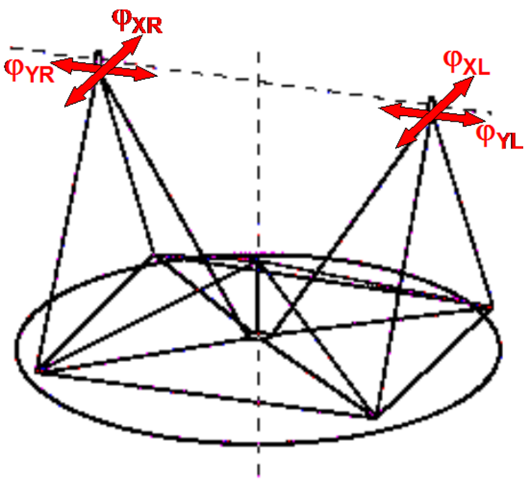
Angular Encoders

Separate housing,
no through hole

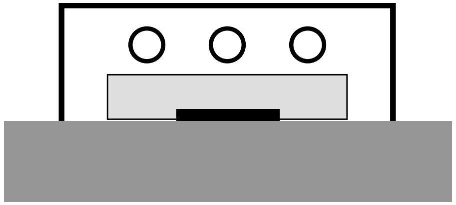
Direct attached,
small through hole

Direct attached,
large through hole

Inclinometers



Temperature Sensors



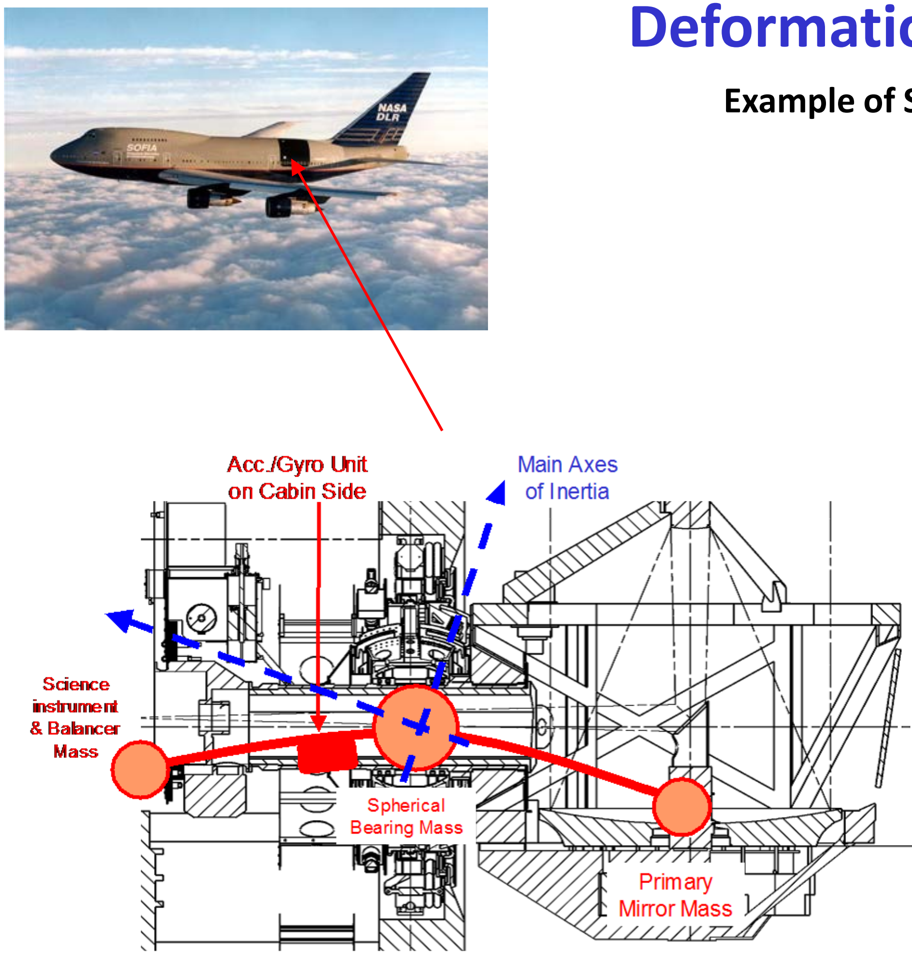
H. J. Kärcher, "Telescopes as Mechatronic Systems",
IEEE Antennas and Propagation Magazine, vol.47, 2005

Metrology Methods Overview

Total Station	Laser Tracker	Photogrammetry
		
Accuracy • Angular 0.5'' • Length 200µm + 2µm/m	**Accuracy** • Angular 1'' • Length 10µm + 5µm/m	**Accuracy** • 5µm + 5µm/m (all directions)
Targets • Coded permanent targets	**Targets** • Mobile retro-reflector	**Targets** • Coded permanent targets

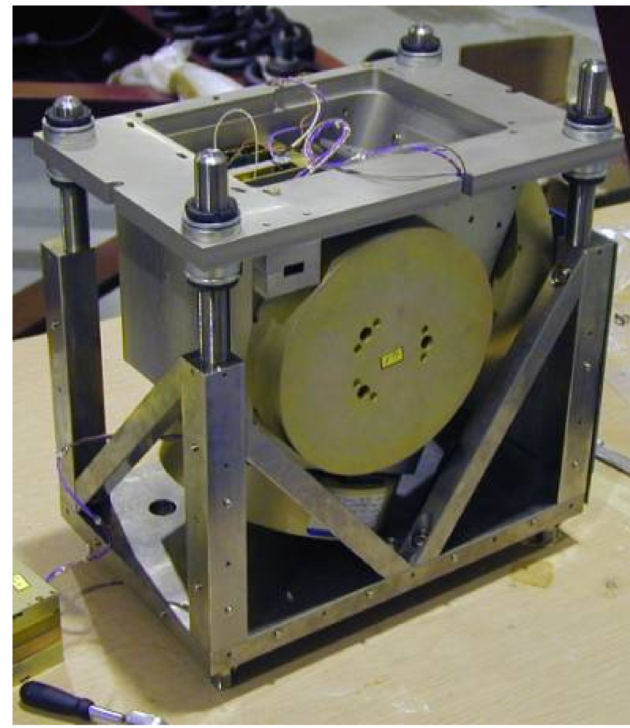
Deformation Sensing III

Example of Sensors



Inertial Stabilization System
SOFIA

Fiber-optical Gyros



H. J. Kärcher, "Telescopes as Mechatronic Systems", *IEEE Antennas and Propagation Magazine*, vol.47, 2005

Structural Mechanics as Theoretical Basis for FBC

The three basic engineering disciplines when designing a telescope:

1. Optics
2. Structural Mechanics
3. Control

Underlying mathematics:

1. Optics => Maxwell's EM theory – ZEMAX/GRASP
2. Structural Mechanics => elasto-mechanics – FEM
3. Control => control theory, transfer functions – MATLAB

Concept for FBC:

Combining “optics”, “structural mechanics” and “control” by a “modal observer”!

Basic mechanical system equations

$$\boldsymbol{M}\ddot{\boldsymbol{q}} + \boldsymbol{D}\dot{\boldsymbol{q}} + \boldsymbol{K}\boldsymbol{q} = \boldsymbol{f}(t)$$

Eigenvalue Problem

$$\boldsymbol{K}\boldsymbol{q}_j^e = \omega_j^2 \boldsymbol{M}\boldsymbol{q}_j^e$$

"Orthogonality" of the eigenmodes

$$\boldsymbol{q}_j^e \boldsymbol{K}\boldsymbol{q}_k^e = k_{jk} \qquad \boldsymbol{q}_j^e \boldsymbol{M}\boldsymbol{q}_k^e = m_{jk}$$

Time dependency

Distinguishing "Dynamic Regimes"

I. The Rigid Body Regime

II. The Quasi-static (= steady state) Regime

III. The Flexible Body Regime ("Jitter")

"System identification" – Modal Survey Test

Sensor placement

$$n^S > n^M \qquad \boldsymbol{x}_k^S; k = 1,2, \dots, n^S$$

Sensor readings

$$s_k(t) = \sum_j S_{kj}\, e^{i\omega t - \varphi_j} = \sum_j q_j\, s_{kj}\, e^{i\omega t - \varphi_j}$$

"Observability"

$$\boldsymbol{q}(t) = \sum_j \boldsymbol{q}_j^e \sum_k S_{kj}^{-1} s_k(t)$$

"Modal Observer" Concept

Also for the quasi-static regime

$$\cancel{\boldsymbol{M}\ddot{\boldsymbol{q}}} + \cancel{\boldsymbol{D}\dot{\boldsymbol{q}}} + \boldsymbol{K}[\boldsymbol{q} - \boldsymbol{q}^T(\cancel{t})] = \boldsymbol{f}^G(\cancel{t}) + \boldsymbol{f}^W(\cancel{t})$$

Quasi-static regime

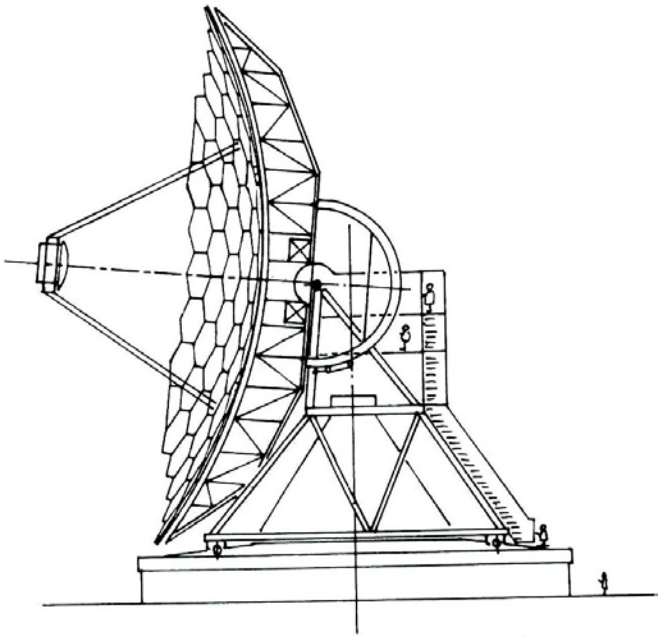
$$=> \boldsymbol{K}\left[\boldsymbol{q} - \boldsymbol{q}_{qs}^T\right] = \boldsymbol{f}_{qs}^G + \boldsymbol{f}_{qs}^W$$

Requirements

FBC
Example LMT/GTM

- HWFE better 75µm rms
- Pointing at operational conditions 1.0 arcsec rms
- Maximal operational wind speed 10m/s

During Design

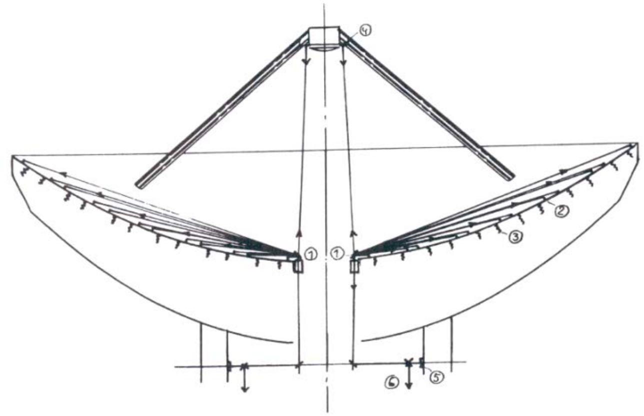


During Commissioning

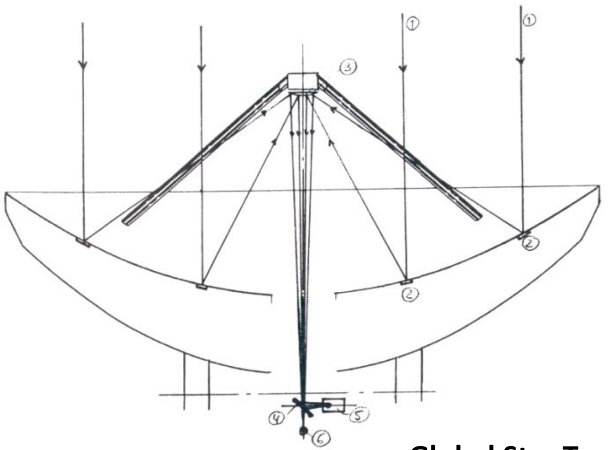
MT MECHATRONICS

LMT “Exposed” Design Study 1997

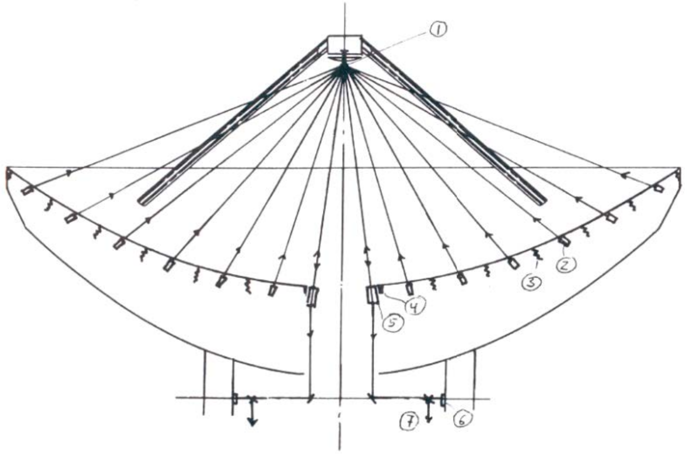
Active Surface Trade-off
MAN June 1997



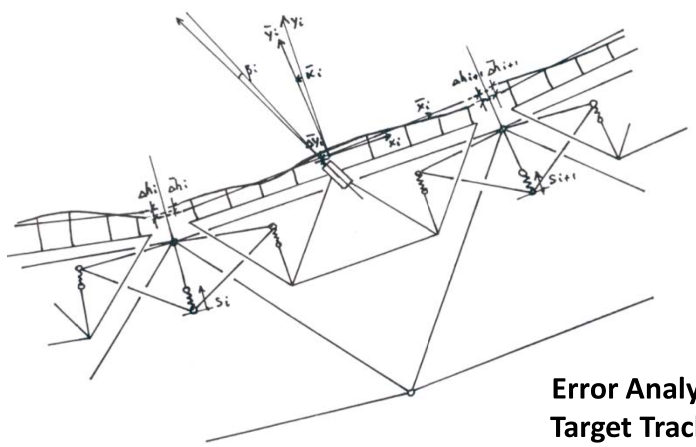
Scanning Mirror Principle



Global Star Tracker Principle



Target Tracker Principle

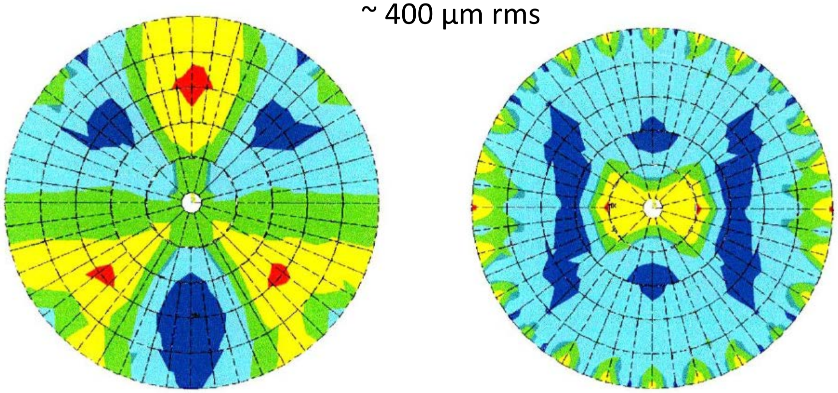


Error Analysis Target Tracker

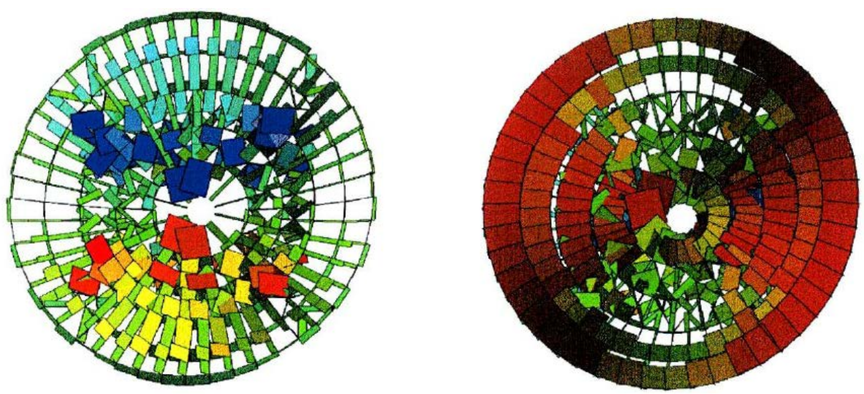
LMT "Exposed" Design Study 1997

Gravity Deformations

~ 400 µm rms



Horizon   Zenith



Strains in Backup Structure

Active Surface Trade-off
MAN June 1997

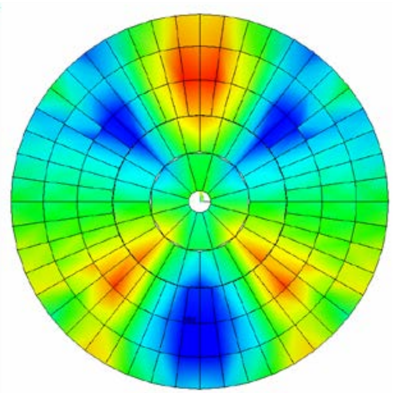
Use of strain gauges for the identification of deformation states?

Later abandoned and replaced by lookup tables.

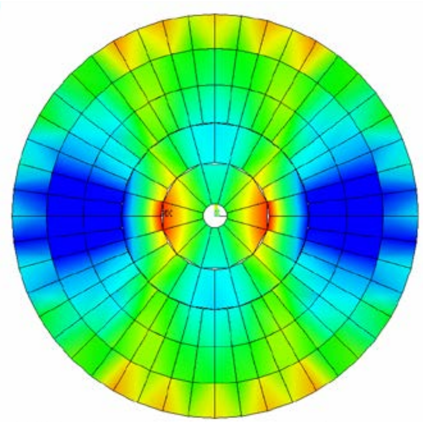
Main Reflector Backup Structure

Structural Optimization MAN 1998

Gravity Deformations



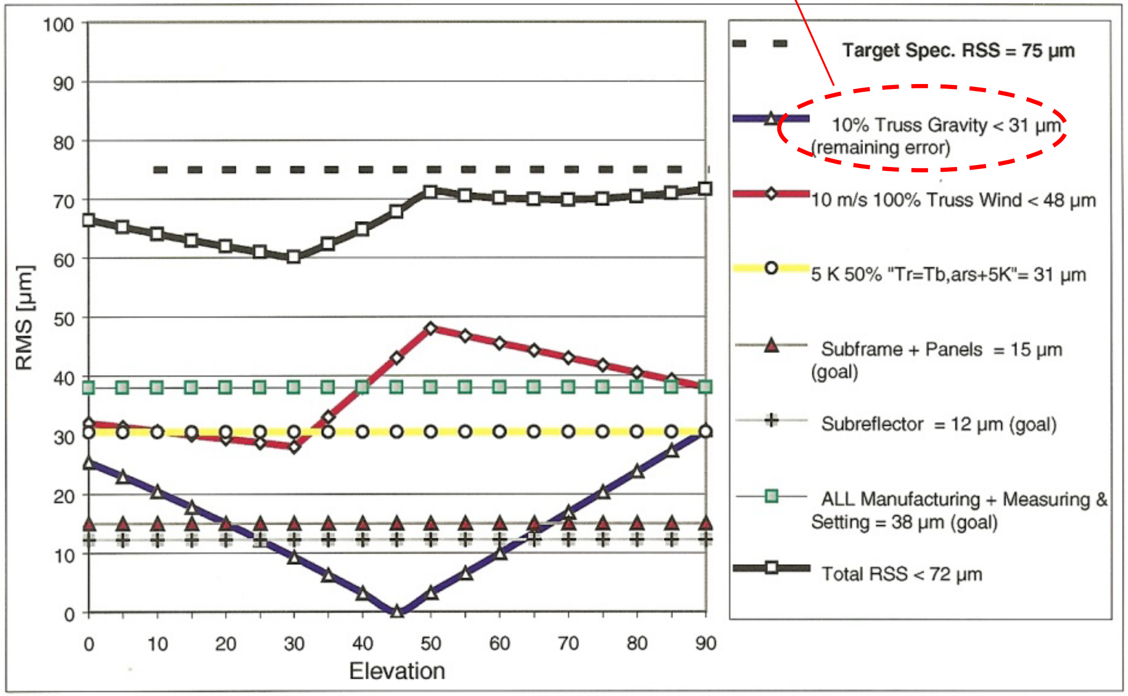
Horizontal Position
415 µm rms



Zenith Position
316 µm rms

FBC of the gravity deformations
via Lookup Tables

HWF Error Budget



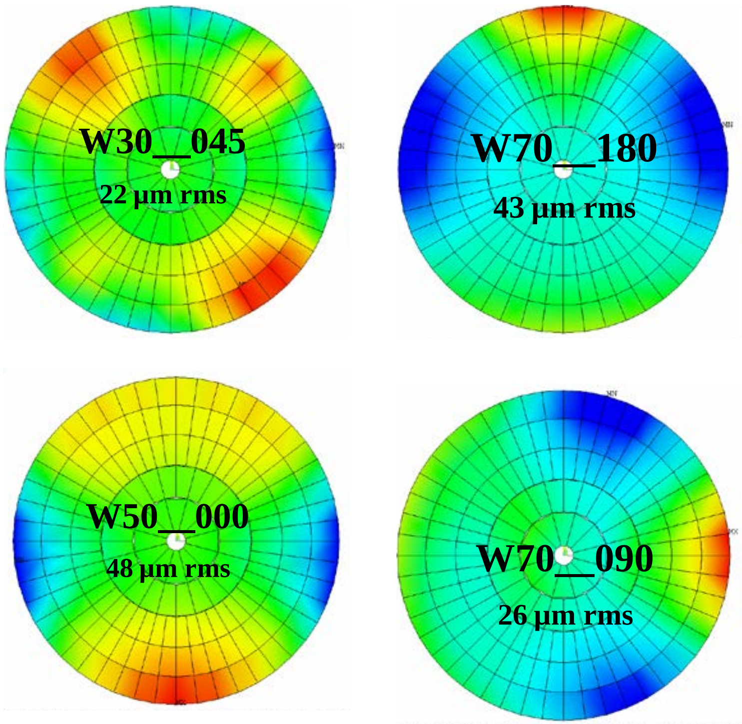
10 m/s (static) Normal Operation	**2.5 K** Temp. Difference	**38 µm** Manu. + Meas. & Setting

Main Reflector Backup Structure

Structural Optimization MAN 1998

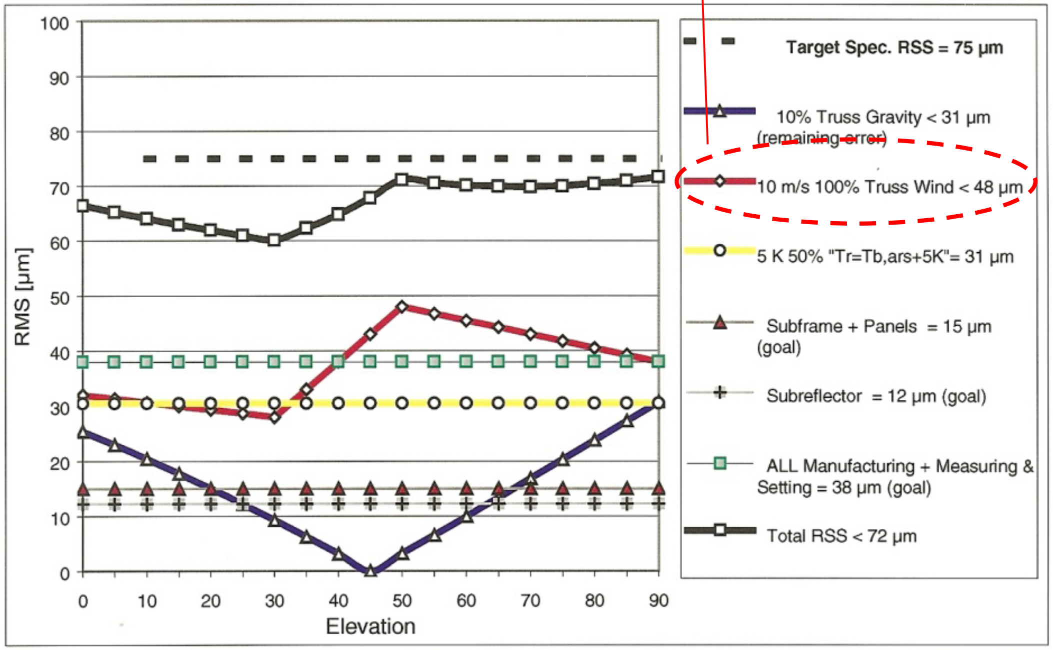
Wind Deformations

Deformation patterns
10m/s operational wind speed



Passive in the limits, no FBC!

HWF Error Budget

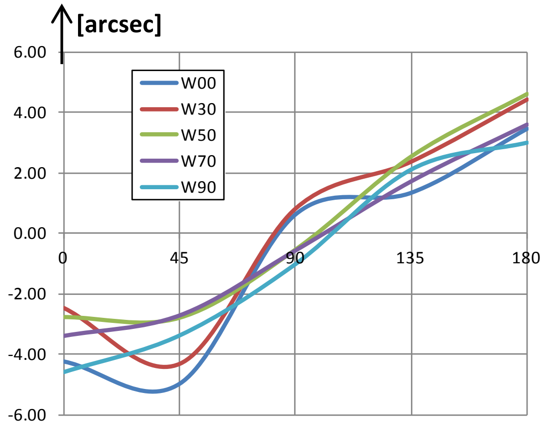


10 m/s (static) Normal Operation	**2.5 K** Temp. Difference	**38 µm** Manu. + Meas. & Setting

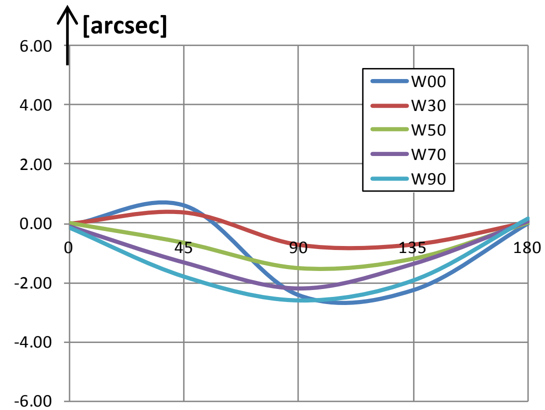
Improvement of the Blind Pointing by FBC with Inclinometers

10m/s operational wind speed

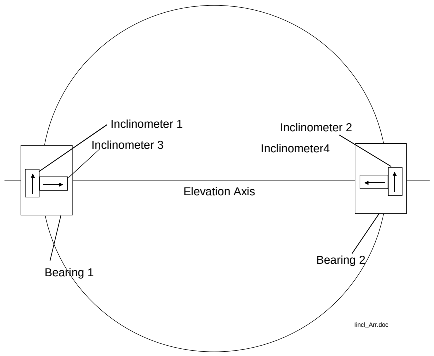
EL

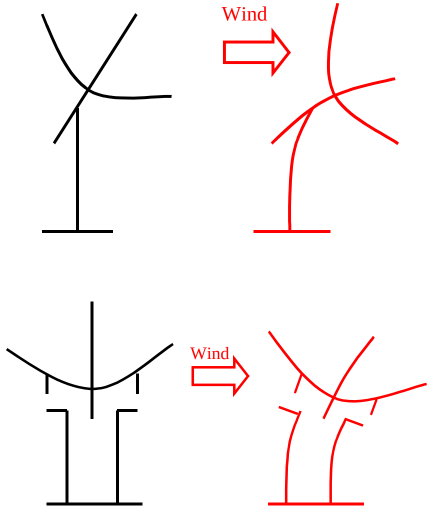


XEL

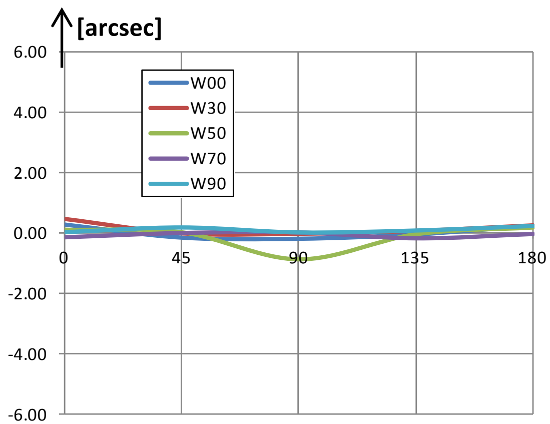


Placement of the Inclinometers

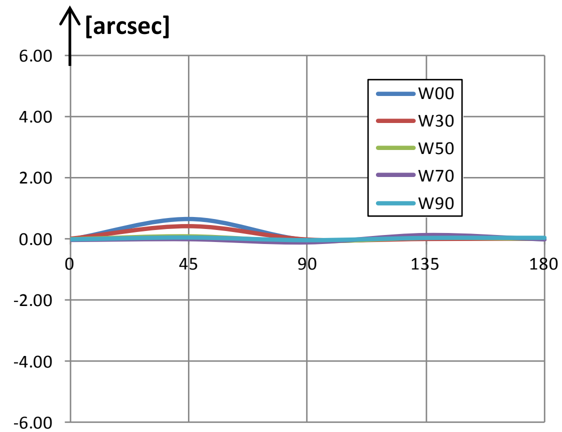




EL FBC



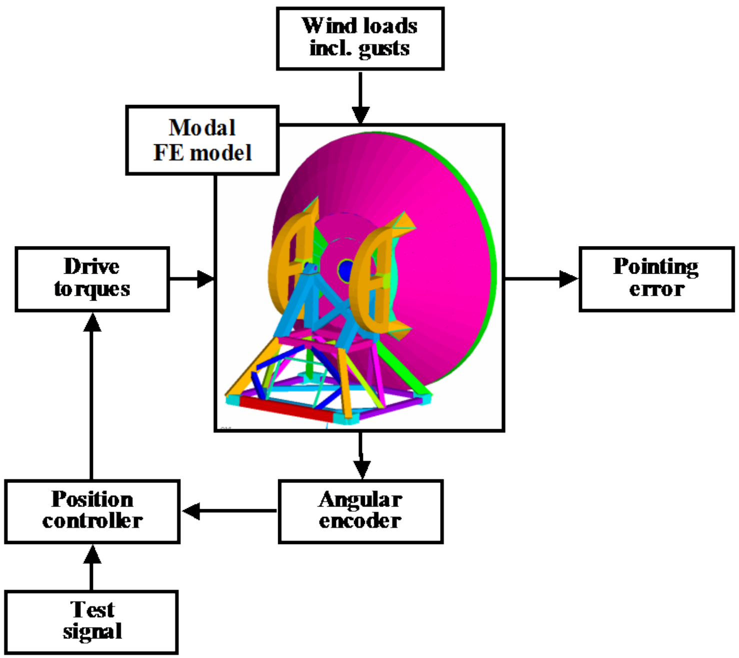
XEL FBC

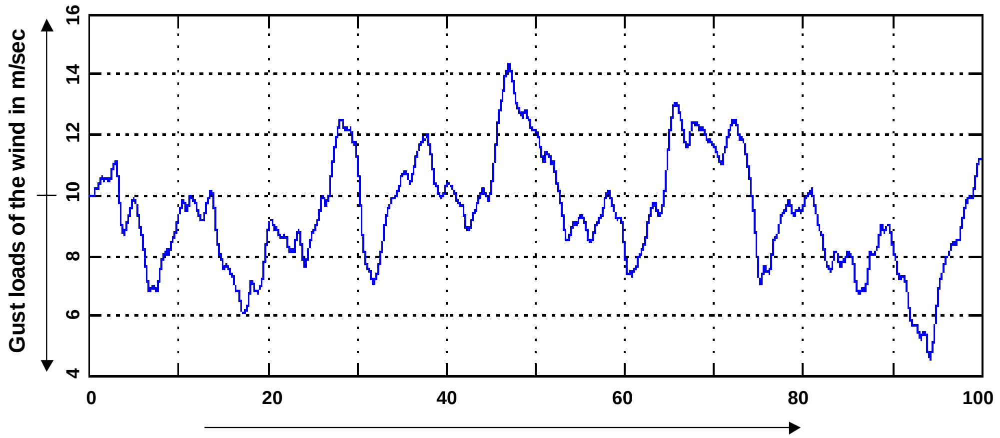


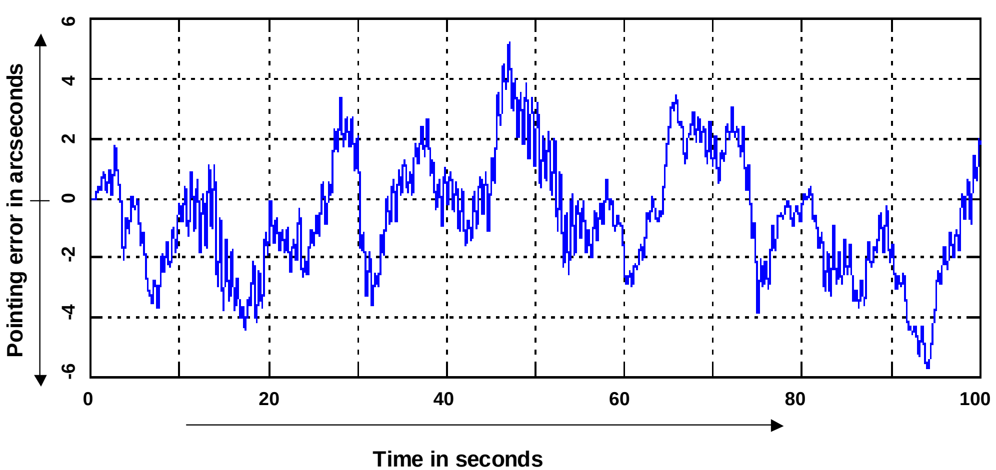
"Jitter"

End-to-end Simulation

Wind on Pointing, Time Domain



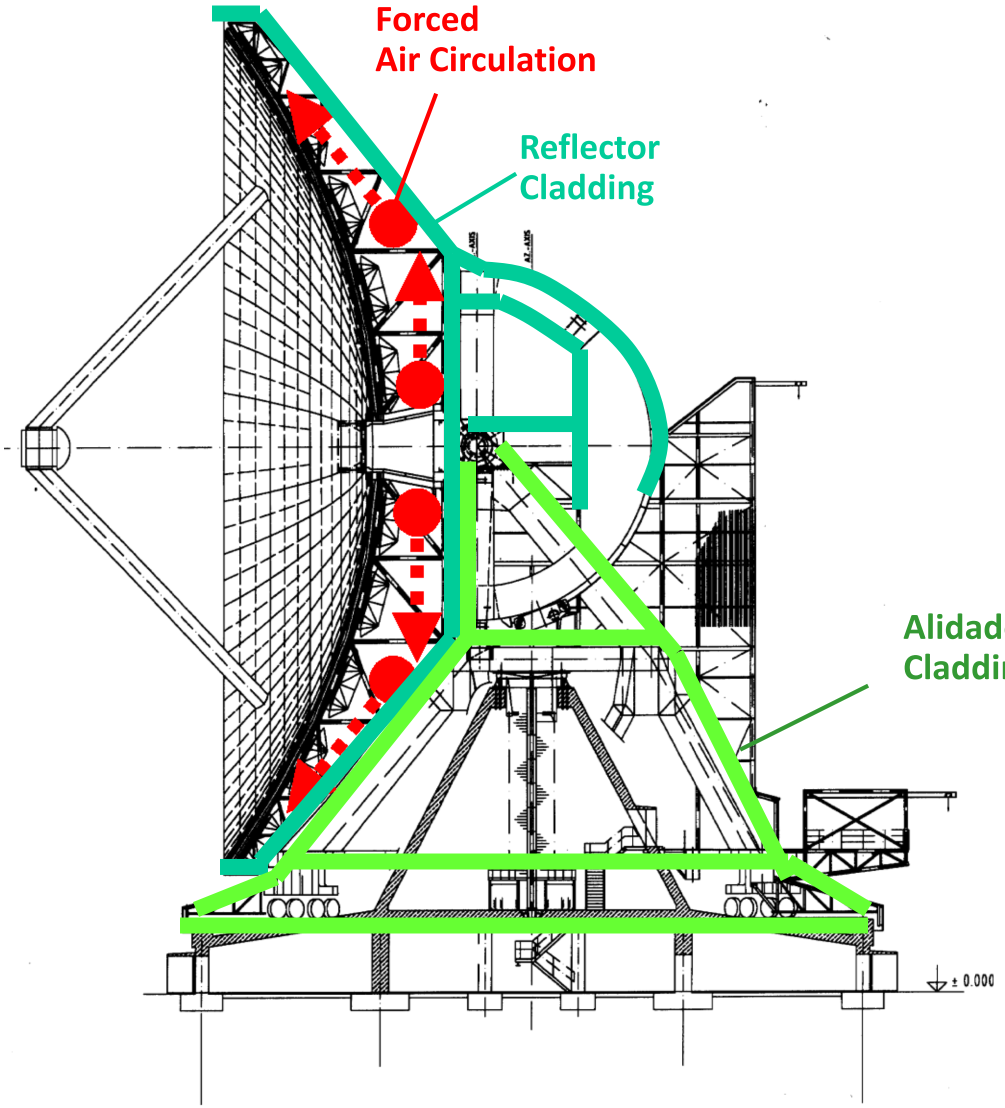




MT MECHATRONICS

Example LMT/GTM

Thermal Subsystem



Thermal Time Constants

$$\tau = \frac{C}{H}$$

Backup Structure	9,4 h
Ballast Arms	53,7 h
Alidade	69,0 h

MT MECHATRONICS

Example LMT/GTM

Error Budgets Design Phase

Surface Accuracy
(µm rms)

Source and Type of Error	Uncorr.	Corr.	Corr. Tech.
Environmental Influences (steady-state)			
a) Gravity Deformations			
BUS	168	17	LUT
Panels	15	15	
b) Wind Deformations (10 m/sec)			
BUS	44	**44**	
Panels	6	6	
Subreflector lateral offset	14	14	
Subreflector defocus	6	6	
c) Thermal Deformations			
BUS	61	20	ThM
Panels	10	10	
Reflector Manufacturing			
Panels	15	15	
Subreflector	15	15	
Mechanical Alignment			
Panels	15	15	
Subreflector	15	15	
Margin		25	
Overall Surface Error Budget		**69**	

Pointing Accuracy
(arcsec rms)

Source and Type of Error	Uncorr.	Corr.	Corr. Techn.
Environmental Influences (steady-state)			
a) Gravity Deformations			
Foundation	<<	<<	
Alidade	<<	<<	
BUS	< 10	(0,2)*	LuT
b) Wind Deformations (10 m/sec)			
Foundation	<<	<<	
Elevation	0,6	0	MoO
Cross Elevation	2,2	0,1	MoO
c) Thermal Deformations			
Foundation	<<	<<	
Alidade	< 1,0	(0,2)*	ThM
BUS	< 1,0	(0,2)*	ThM
d) FBC Uncertainty		0,3	
*) : included in "FBC Uncertainty"			
Environmental Influences (Dynamic)			
Wind 10 m/sec :			
Gusts on Servo	0,3	**0,3**	
Gusts on Structure	0,2	**0,2**	
Mechanical Alignment			
Overall	5,0	**0,5**	ACM
Servo			
a) Sensors			
Encoder precision	0,07	0,07	
Encoder Couplings	0,07	0,07	
b) Actuators			
Backlash of drive units	5,00	0,03	DPT
Friction variation	1,00	**0,30**	DFF
Motor cogging	0,03	0,03	
Drive unbalance	0,03	0,03	
Servo amplifier offset and noise	0,03	0,03	
c) Servo Controller	0,03	0,03	
d) Servo Commands			
Velocity lag	5,00	0,02	DTG
Acceleration lag	3,00	0,05	DTG
Program track interpolation	0,02	0,02	
Time synchronisation	0,02	0,02	
Margin		0,30	
Overall Pointing Error		**0,82**	

Look Up Table

Modal Observer

Thermal Model

Astronomical Pointing Model

Drive Pretension Disturbance feed Forward

Dynamic Trajectory Generator

Example LMT/GTM

Verification after Commissioning

SPIE 9906, 2016

Calibration and Operation of the Active Surface of the Large Millimeter Telescope

F. P. Schloerb[a], D. Sanchez[b], G. Narayanan[a], N. Erickson[a], K. Souccar[a], G. Wilson[a], D. Gale[b], D. H. Hughes[b], and D. Smith[c]

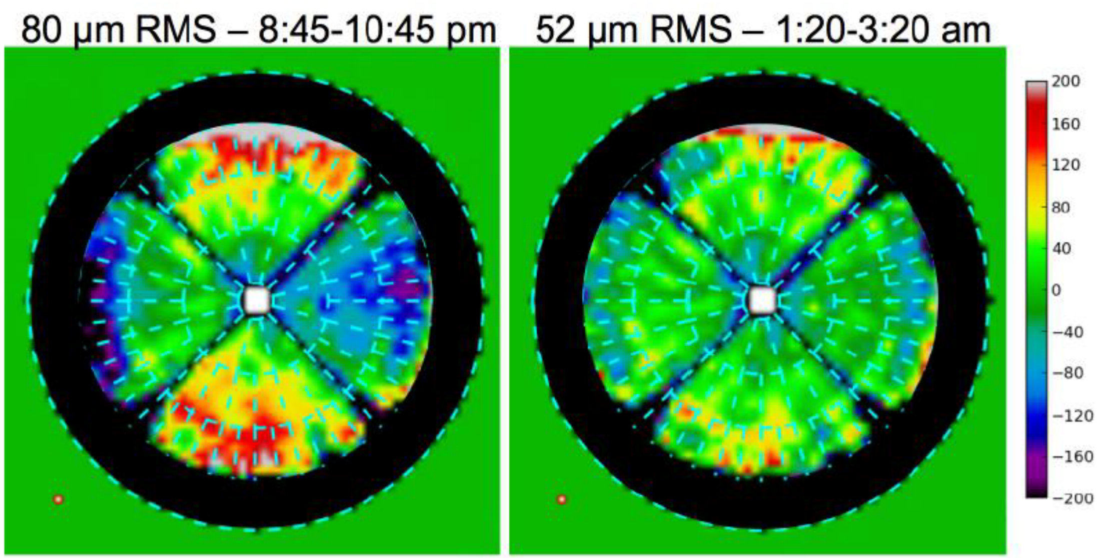
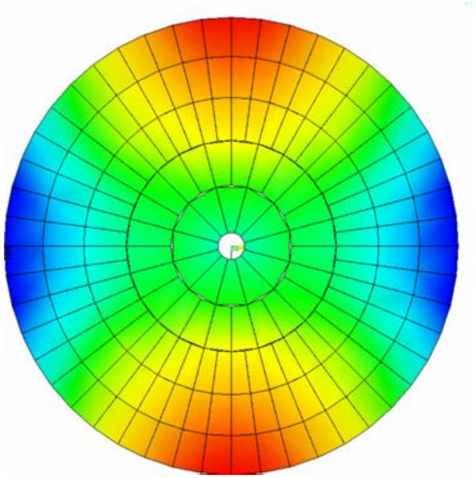


Figure 2. Holography maps of the LMT surface at elevation 43 degrees obtained at two different times during the night. The map on the left was obtained between 8:45 and 10:45 pm local time. The map on the right was obtained later between 1:20 and 3:20 am. There is an apparent systematic change in the shape of the surface that occurs as the surface cools during the night. The colorbar at the right hand side of the figure indicates the local deviation from the best parabola. The prominant "X"in the image occurs where the secondary support structures block the satellite signal leading to a serious degradation of the surface measurement.

From MAN Analysis Report, 2000



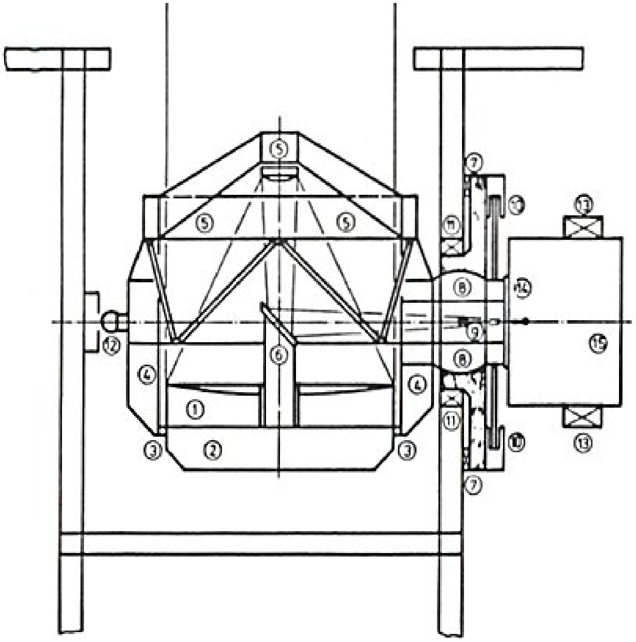
ΔT = 5° between Alidade and Elevation Structure 28 µm rms

Example SOFIA

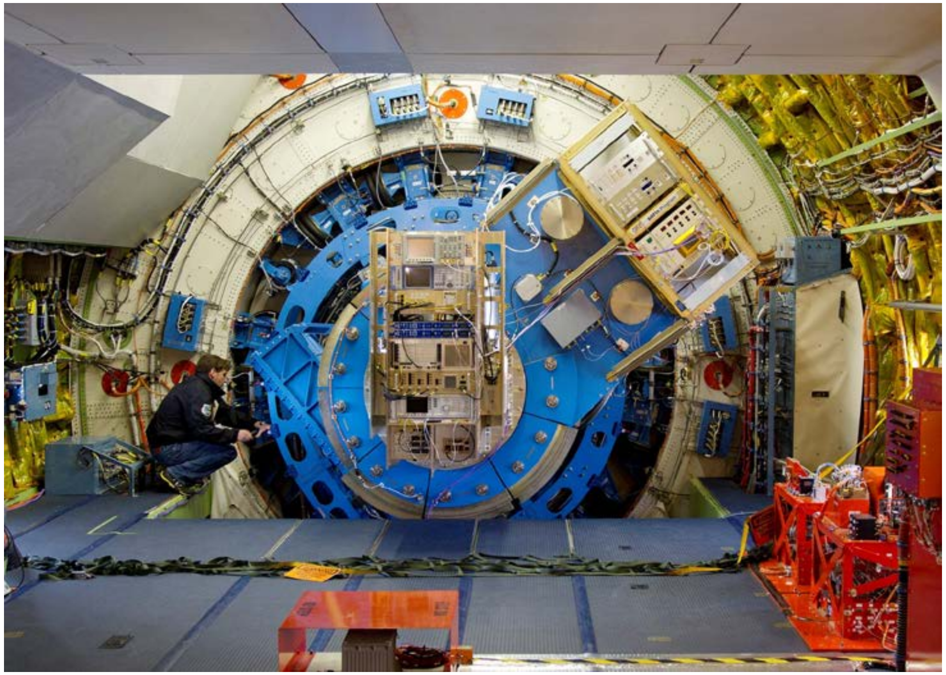
Pointing Requirement

0.4 arcsec rms

Design Concept 1987



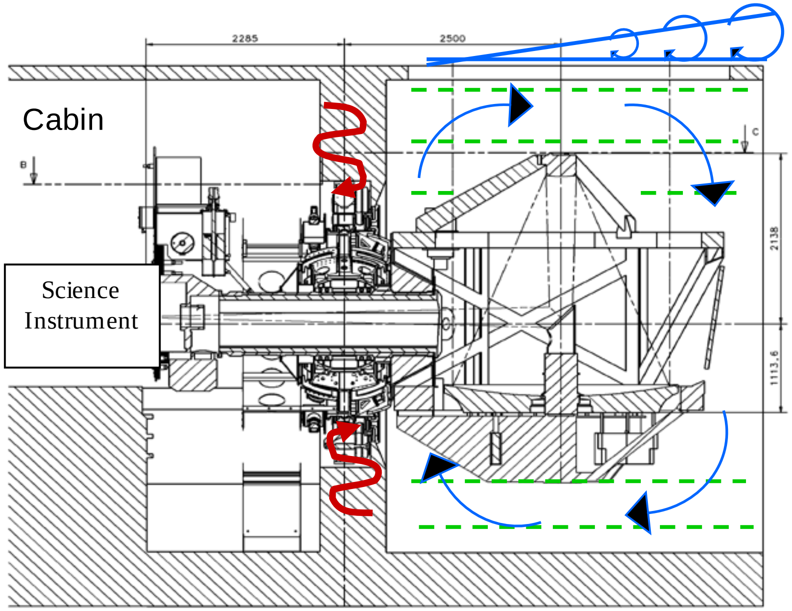
After Commissioning



FBC
Example SOFIA

Pointing Requirement
0.4 arcsec rms

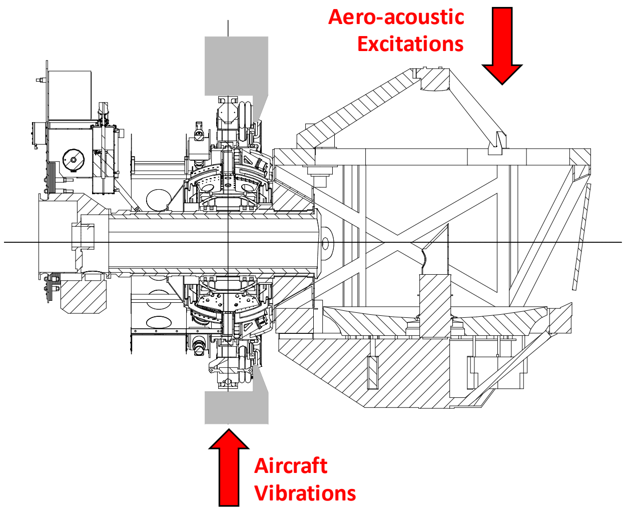
During Design



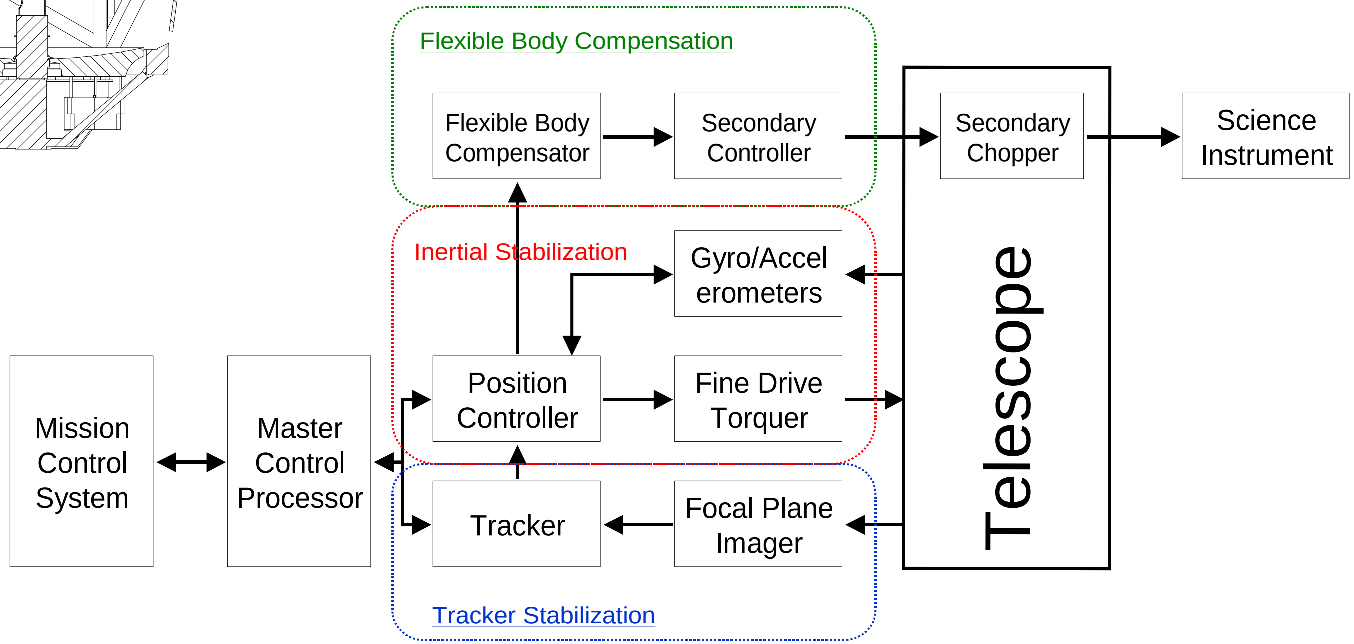
During Commissioning

SOFIA

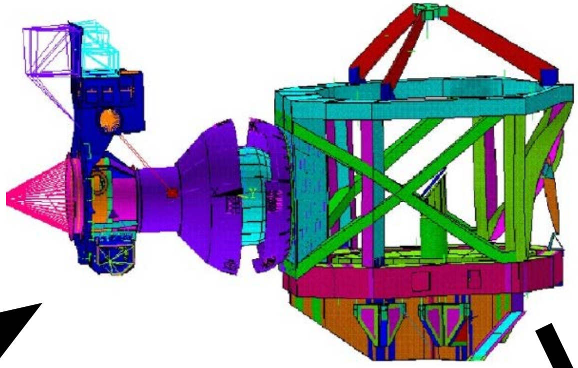
Pointing Requirement
0.4 arcsec rms

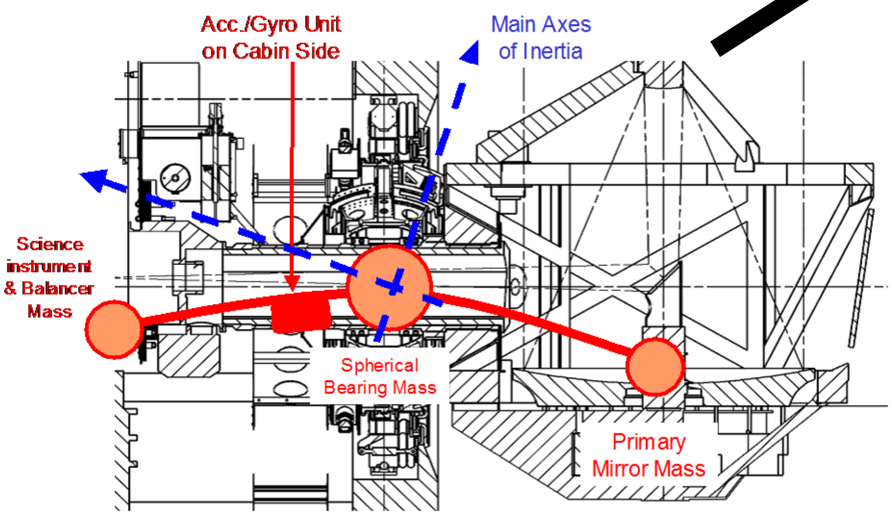


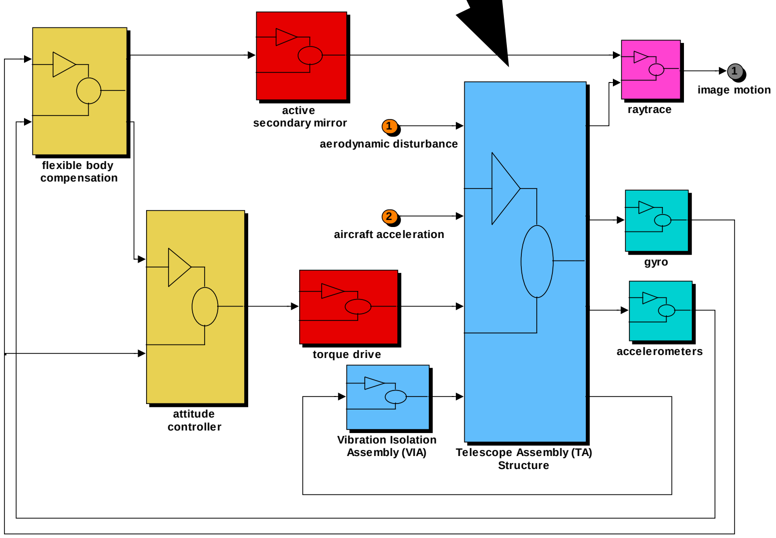
Overview on the Pointing Subsystem



Inertial Stabilization System of SOFIA

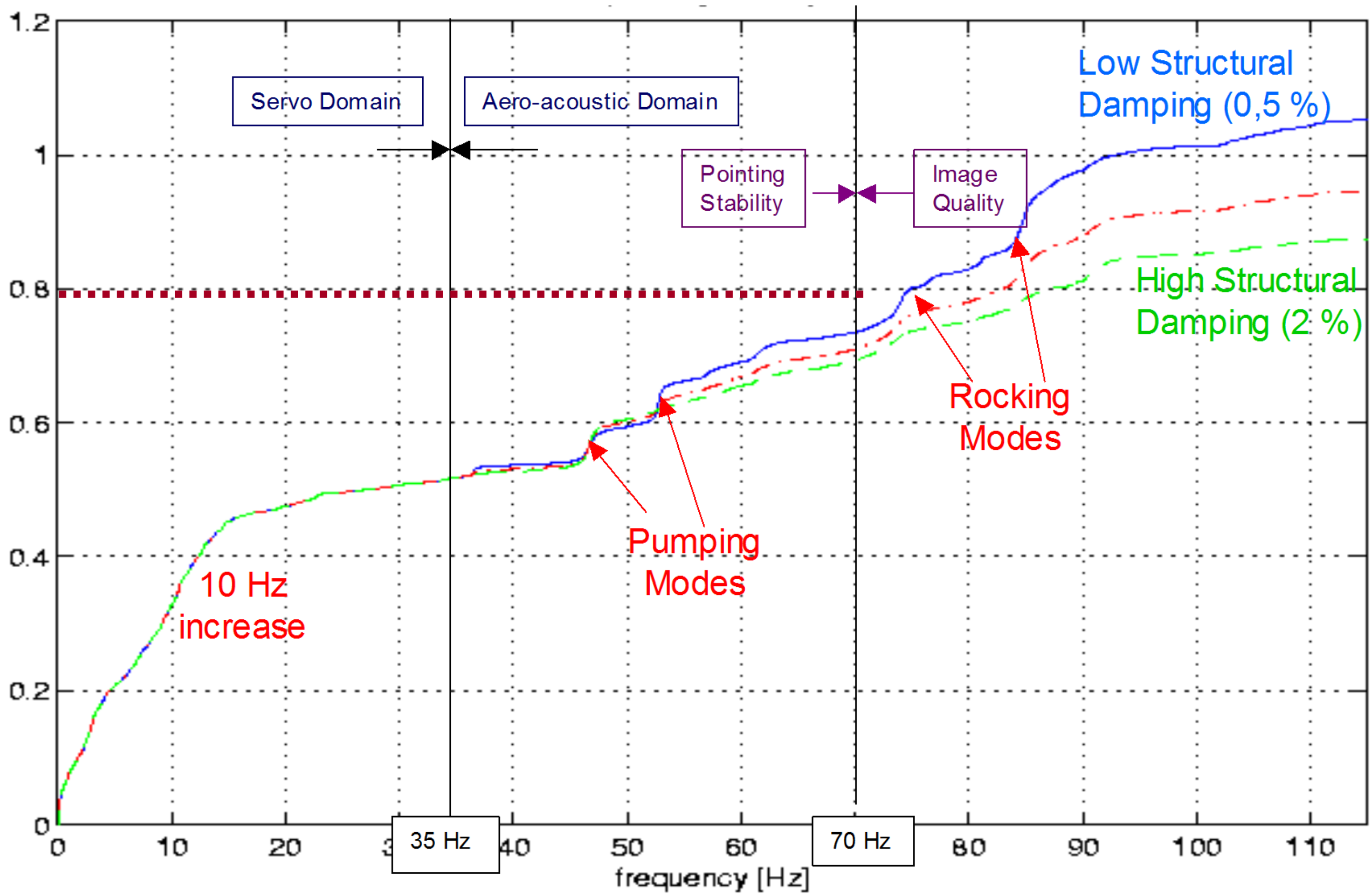






MT MECHATRONICS

SOFIA End-to-end Simulations Pointing
CDR Status



MT MECHATRONICS

SOFIA Pointing Budgets CDR Status

Subsystem Contributions

Table 1 Pointing Stability Budget Telescope Subsystems		Error Contribution
Telescope		
1.	**Tracking Loop**	
1.1	Tracker stability (imagers etc.)	0,05
1.2	Aliasing	0,03
1.3	Gyro random walk	0,05
1.4	Gyro drift estimation	0,03
Error per Row 1. (RSS)		**0,08**
2.	**Inertial Stabilization Loop**	
2.1	Telescope disturbances	
2.1.1	Cradle Couplings (coarse drive,	0,04
2.1.2	Balancer Drives (stick/slip etc.)	0,02
2.1.3	Overall Imbalance (mismatch	0,02
2.2	Gyro resolution	0,01
2.3	Fine Drive (Torquer ripple etc.)	0,07
2.4	Fine Drive Controller Noise	0,03
Error per Row 2. (RSS)		**0,09**
3.	**Secondary Mirror Assembly**	
3.1	SMA position stability	0,05
Error per Row 3. (RSS)		**0,05**
4.	**Alignment**	
4.1	Dynamic Misalignment SI - FPI	0
4.2	Coordinate transformation error FPI -	0,02
4.3	Coordinate transformation error Gyro	0,02
Error per Row 4. (RSS)		**0,03**
Error per Row 1. - 4. (RSS)		**0,14**

Environmental Influences

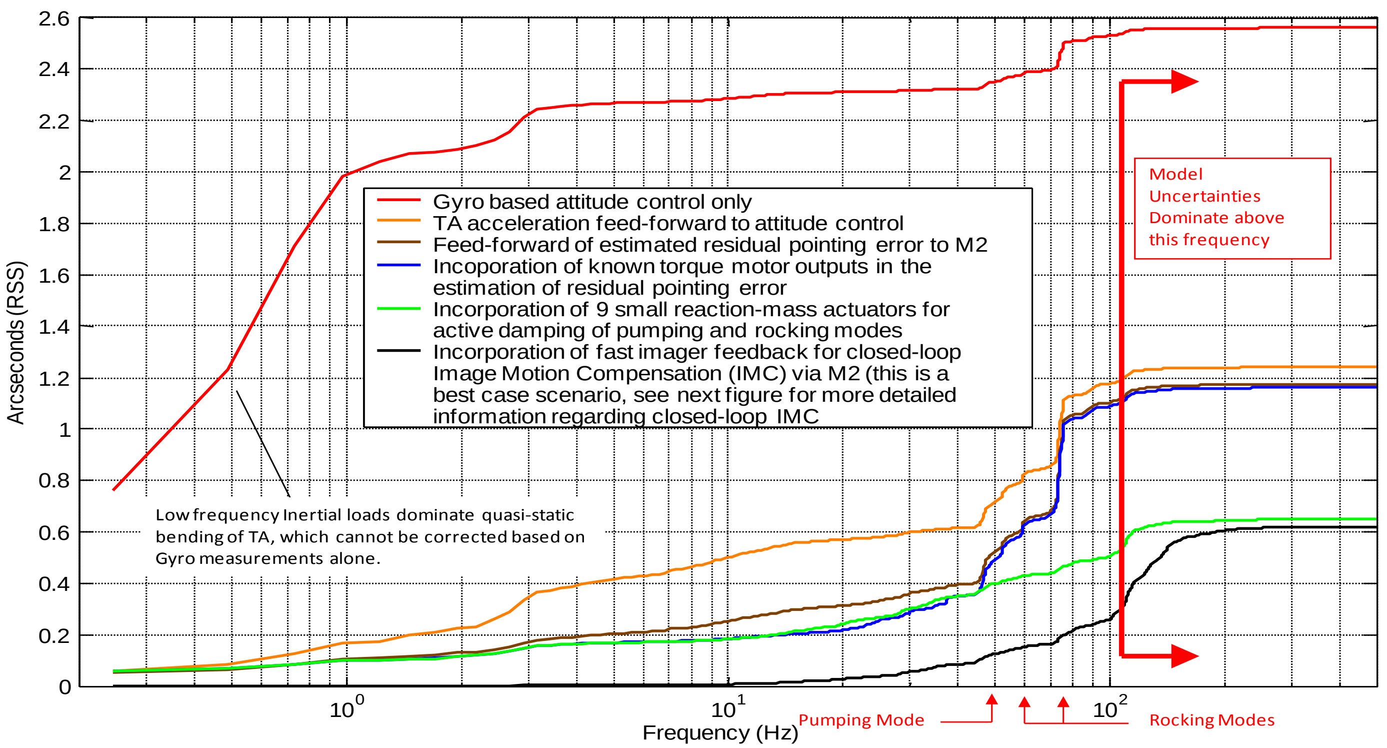
Table 2 Pointing Stability Budget Aircraft Environment		Freq. 0-10Hz	Freq. 0-35Hz	Freq. 0-70Hz	(Freq. 0-110Hz)
Subsystems		**0,14**	**0,14**	**0,14**	**0,14**
5.	**Flexible Body Compensator**				
5.1	FBC Sensors (accelerometers)	0,04	0,04	0,04	0,04
5.2	FBC Actuators				
5.2.1	Fine Drive	0,07	0,07	0,07	0,07
5.2.2	SMA	0	0,05	0,05	0,05
5.3	FBC Controller (estimation error)	0,04	0,04	0,04	0,04
Total FBC Subsystems		**0,09**	**0,10**	**0,10**	0,10
6.	**Thermal Effects**				
6.1	Focal Plane Imager	0	0	0	0
6.2	Tertiary Mirror	0,02	0,02	0,02	0,02
Total Thermal Effects		**0,02**	**0,02**	**0,02**	0,02
7.	**Aircraft Vibrations**				
7.1	0-10 Hz	0,16	0,16	0,16	0,16
7.2	10-30 Hz		0,25	0,25	0,25
7.3	30-70 Hz			0,09	0,09
7.4	70-110 Hz				0,04
Total Aircraft Vibrations		**0,16**	**0,30**	**0,31**	0,31
8.	**Aerodynamic Loads**				
8.1	0-10 Hz	0,30	0,30	0,30	0,30
8.2	10-30 Hz		0,40	0,40	0,40
8.3	30-70 Hz			0,49	0,49
8.4	70-110 Hz				0,85
Total Aerodynamic Loads		**0,30**	**0,50**	**0,70**	1,10
Commands					
9.	**Tracking Commands**				
9.1	Non-inertial tracking	0	0	0	0
Total Command Influences		**0,00**	**0,00**	**0,00**	0,00
Total Pointing Error (RSS)		**0,38**	**0,61**	**0,79**	1,16

Manufacture, preassembly, pre-shipment tests 1999-2001 in Augsburg
Integration into aircraft 2002-2003 in Waco

SPIT Activities 1999 to 2002

- “SOFIA Pointing Improvement Team”, co-chaired by Hans Kärcher and Nans Kunz
- SPIT Workshop 2000 on mechanical improvements in Mainz
- SPIT Workshop 2001 on “Image Motion Compensation” in Berkeley

Pointing improvement predictions SPIT October 2001



FBC
Example SOFIA

In-flight improvement after commissioning

See separate presentation by Friederike Graf SPIE 9906, 2016

FBC
Example DKIST

Wind induced Pointing Error < 0.1 arcsec rms
“Jitter” < 0.075 arcsec

Jitter tests on IMT Gantry machine

Factory Acceptance Tests