Coarse Pointing and Fine Pointing Mechanism (CPA and FPA) for an Optical Communication Link

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Structure and Mechanism Section

1 ABSTRACT

Future multimedia satellites require communication at large bandwidth which can be achieved by means of optical communication links. Astrium (TESAT) is currently developing a Laser Communication Terminal (LCT) for such applications under DLR contract.

In 2002 the mechanisms for Pointing, Acquisition and Tracking of the laser beam between two Laser Communication Terminals were pre-developed. Based on this development work the development of mechanism H/W to be flown on TERRASAR is currently under way.

After a short description of the general arrangement of the Mechanisms inside the LCT, the paper describes the design of the CPA (Coarse Pointing Assembly) and of the FPA (Fine Pointing Assembly) reflecting the critical requirements and the solutions how to achieve them. The third mechanism forming the LCT mechanical equipment is the PAA (Point Ahead Assembly). Since the only difference between PAA and the FPA are the different tilt range and accuracy, the PAA will not be discussed specifically.

2 INTRODUCTION

Due to the fact that the goal of the program is the development and in-orbit verification of a low cost laser terminal which has to be delivered in a very short time frame, off the shelf components adapted to space needs are used as far as possible in the mechanisms. Potentially applicable commercial components have been identified, and the associated qualification risk was assessed.

The design features of the CPA drive units (such as drive and bearing concept, mirror support concept) and of the FPA (e.g. design of the spherical motor used for high bandwidth application) are described. The design is supported by functional and performance tests carried out on an existing DM mechanism H/W.

3 FUNCTIONAL ARRANGEMENT OF THE PAT MECHANISMS

The CPA is located on the outer mounting interface of the Frame Unit Structure (FUS) which is arranged parallel to the satellite panel (see Fig.: 3-1. The special arrangement of the hollow drive units and of the flat mirrors allow to point the laser beam hemispherically. The CPA is mounted above the TLA (Telescope Assembly) to the FUS. The task of the TLA is to bundle the received (incoming) laser beam from the opposite terminal and to expand the transmitted (outgoing) laser beam to a diameter of 136 mm. The major part of the TLA as well as the FPA and PAA are located inside the terminal and will not be exposed to extreme temperatures during sun exposure and eclipse. The CPA in contrast is exposed to sunlight and also to eclipse temperatures and will therefore be protected by Multi Layer Insulation (MLI). During launch the CPA is in its (dust protected) park position with its aperture facing towards the Park Position Assembly (PPA) and locked by the Launch Locking Device (LLD).

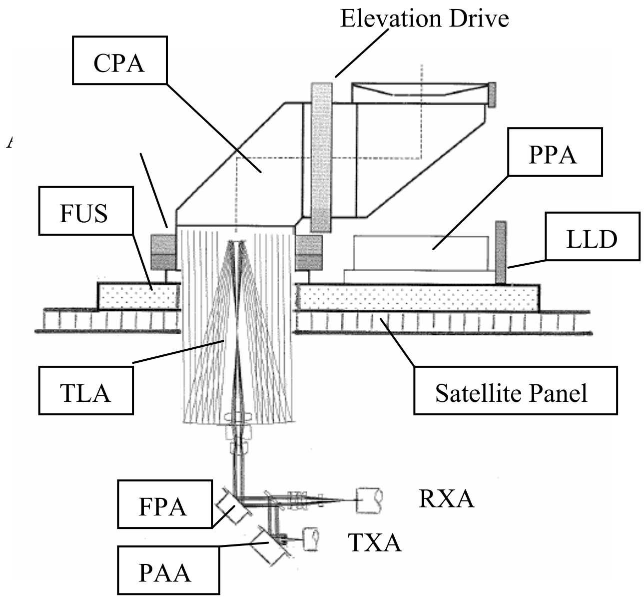

Fig.: 3-1 Functional Arrangement of the PAT Mechanisms

4 PRE-DEVELOPMENT PHASE

Prior to the start of the running flight H/W development phase Astrium developed and produced a test model of the CPA and FPA in the frame of a short pre- development phase. Due to the limited budget and tight schedule (about 6 months) of the pre-development phase, no very detailed analysis or environmental tests could be performed on the DM mechanisms. However some performance measurements and tests gave important feedback for the running flight equipment development phase. The most important findings resulting form the pre-development phase are described in the following.

CPA Drive Unit:
Thermal tests with a DM drive unit have been performed at -40°C and +55°C. The calculated max. friction of the drive unit bearing system of 0,4 Nm at -40°C could be verified by test. During functional testing the customised commercial servo motor showed that the torque as well as the performance together with the controller was excellent and requires no design change.

The encoder read-out head of the industrially procured 21 bit encoder has passed the temperature tests as well, the signal levels were in specification and no count errors occurred during the whole test. However during the high temperature case the encoder did not pass the tests, a creeping effect between metal encoder ring and the glued-on incremental foil caused an offset of the reference mark position. The resulting gap at the glued ends of the incremental foil was not acceptable. In addition it was found that the (industrial) manufacturer was not willing to provide the information required to modify the encoder for flight s application, so that in this point a redesign activity and change to a different encoder manufacturer was requested.

CPA Mirror Unit:
In the pre-development phase the design and production of the mirrors was performed and the mounting interfaces have been designed. During alignment of the mirrors it became obvious that the mirror support device (isostatic mounts) were strongly influencing the mirror surface accuracy. On basis of this finding a detailed structural analysis was started at begin of the project. Analysis showed that the stiffness of the mirror was far too low and the stiffness of the isostatic mounts much too high to achieve a stability in the range of 10 nanometers RMS over the whole operational temperature range.

FPA Design:

The Design has been verified by function and performance tests. The optical performance of the mirror (< 20 nm RMS) was achieved and the closed loop bandwidth of 4000 Hz could be verified. A further important outcome of the performance tests was that the accuracy is limited by the noise of the Kaman sensor and was not in specification. The jitter of the Kaman sensor was about 3,5µm and did not fulfil the jitter requirement of < 2µm. Nevertheless this sensor has been identified as the most suitable sensor for the application and is procured at an early stage of the project for further investigations and performance optimisation on basis of component tests.

5 COARSE POINTING ASSEMBLY (CPA) DESIGN

5.1 Design Requirements

In the following the major Requirements for the CPA are listed. The requirements are all valid under the following environmental boundaries and their combinations.
Solar scan rate: 2deg/min (sun is shining directly into the CPA aperture)
I/F temperature at FUS: - 35°C to +55°C

- Physical Properties
  - Dynamic Envelope: diameter 612 mm, height 322 mm
  - Optical Aperture: 136 mm
  - Mass: < 12 kg
  - Azimuth Range: +/- 200 deg
  - Elevation Range: -30 ... +100 deg
- Performance Data
  - Acceleration: > 4 deg/s2
  - Slew Rate: > 25 deg/sec
  - Abs. Pointing Accuracy: < 125 µrad (RMS)
  - Stiffness: > 150 Hz (launch configuration)
  - Mirror surface: < λ/60 RMS (λ = 1064 nm)

5.2 Design Approach

The function and partially also the performance of the CPA could be verified by tests on the DM model available from the pre-development phase. The following design principles were followed.

- Improvement of the development model design by supporting it by Thermal and Structural Analysis on basis of the given environmental loads.

- Use of commercial components where possible.
- Use of low weight material with similar CTE as the steel-bearings for all structural parts → DISPAL S225

The CPA design established during the pre-development phase was driven by function and accuracy requirements. During this short development phase no detailed FE-model analysis and comprehensive environmental testing have been performed with the complete CPA. However two important findings resulted from this phase.

- mirror fixation has to be improved, the mirror support affects the significantly the mirror wavefront performance.
- commercial encoder failed during thermal test, space qualified encoders are required.
- Structural Material was changed form AlBeMet to Dispal S 225 due to cost and procurement reasons.
- A Cable Wrap has to be added to the azimuth drive to guide the elevation harness down to the base.

These modifications have been implemented in the preliminary design which is described in the following.

5.3 Design Description

The CPA is designed as a stiff and light weight construction used to guide incoming and outgoing Laser-Beams from/to the telescope and instruments located behind the interface panel of the satellite. The aperture of the CPA can be positioned in the required range (hemispherical coverage) by two independent drive units. The beam is guided by two high precision mirrors to hold track of the optical path.
Fig.: 5-1 shows a 3-D view of the CPA in launch configuration.

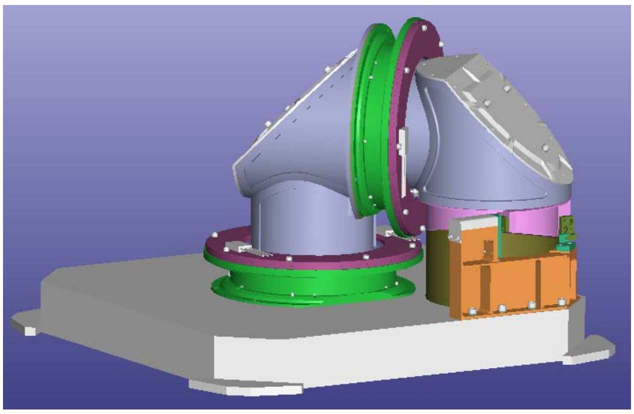

Fig.: 5-1 3-D view of the CPA in launch configuration

The described design of the CPA is driven by the following aspects:

- Minimisation of envelope by using compact drive modules
- Minimisation of mass by using as far as possible lightweight components
- Thermal requirements to be taken into account as conductivity, radiation and isolations at sensitive interfaces
- High bearing stiffness and load capacity (launch) by inclined pair of dry lubricated ball bearings in O-arrangement in each of the drive modules
- Cable Wrap on Azimuth Axis
- Avoidance of stray light effects on the inside the CPA by coating (Plasmocer) and avoidance of backscattering edges
- Light tightness of CPA housing
- Stiff and low weight launch locking device
- External mechanical I/F flange out of Dispal S 225 (similar thermal expansion as AlBe-Met)

Fig.: 5-2 shows a cross section through the CPA in its launch configuration. The main subassemblies are:

- Drive Units
  Housing, Motor, Encoder, Cable Wrap for Azimuth Drive only
- Mirror Units (Azimuth and Elevation)
- Park Position Assembly (PPA)
- Lauch Locking Device (LLD)
- Azimuth- and Elevation structural parts.

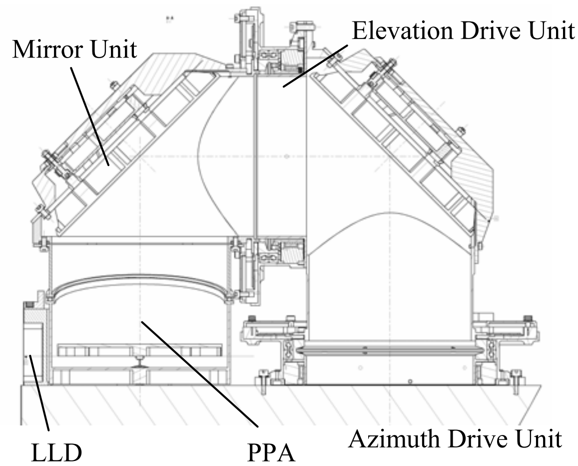

Fig.: 5-2 Cross Section through CPA

5.3.1 Drive Units

Motor
Each CPA drive unit uses a brush-less DC motor (high lifetime) and with the advantage to be programmable for customised application (acceleration, velocity).
The brush-less DC motor (thin-ring Rotor and Stator) will be developed in combination with the Codechamp encoder to achieve the high position accuracy and acceleration as required for the CPA. The encoder signal is not only used to read-out the highly accurate CPU tracking signal, but also to provide the motor with its internal position information for commutation.

Encoder
Screening of available space qualified encoders on the market showed that the high accuracy requirements in combination with the space requirements compatibility at compact design fitting to the application can be achieved by using a Codechamp absolute encoder which has to be modified and adapted to the needs defined by the overall dynamic envelope and the drive unit design.

Bearings
Wet Lubricated ball bearings cannot be used due to out-gassing or oil-creeping concerns. Good experience in terms of low friction in vacuum has been made with MOS2 sputtered steel balls which have the disadvantage of friction increase due to humidity under ambient conditions (purging required before on ground testing). An alternative can be ceramic balls which have a limitation in shock loads but could be used in the envisaged application from this point of view. However analysis showed that the heat conductivity of ceramic ball is not suitable for the application. The general problem with ball bearings is that the thermal conductivity between inner and outer ring, even using steel balls, is poor, so that un-wanted thermal gradient are occurring.

In order to achieve the CPA stiffness requirement and to limit or avoid gapping during launch, the bearings have to be pre-loaded. The pre-load however is limited by the max. allowable operational resistive torque of 0,4 Nm which is fixed by the drive unit design, the available power and the required torque margin. This limitation in resistive torque leads to a max. allowable gradient between inner and outer ring of the ball bearings of about 5°C. To achieve this small gradient under the extreme temperature difference between fixed and moved structures without using additional heaters was one of the most challenging tasks in the development phase.

The following worst case scenarios have to be covered by the CPA design:

Hot Case:	Sunlight with a solar scan rate of 2°/min at the CPA structure and mirrors I/F temperature at FUS is -35 °C
Cold Case:	Deep Space I/F temperature at FUS is +55 °C

In order to achieve the requirement on the thermal gradient between inner and outer bearing ring of <5 °C, the following thermal hardware and mechanical design improvements as shown in Fig.: 5-3 have been analysed:

Pos. 1	Thermal Washers (GFRP, thickness 4mm)
Pos. 2	MLI (TBD Layers)
Pos. 3	Plasmocer black
Pos. 4	Thermal Tape
Pos. 5	Thermal Paint
Pos. 6	Radiation Tube (El-Drive) , Telescope Tube (Az-Drive)

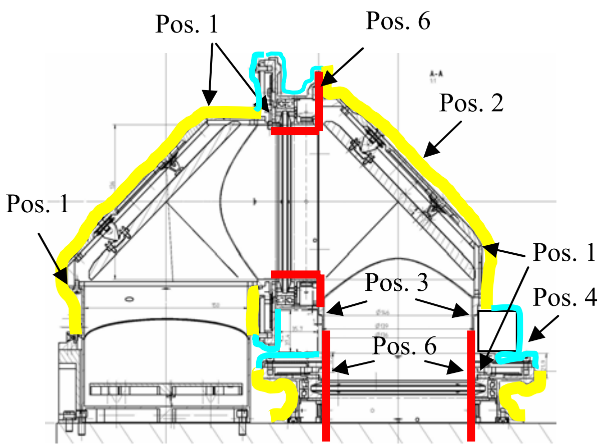

Fig.: 5-3 CPA Thermal Hardware

Taking into account all these measures, the required gradients between the bearings inner/outer ring, can be achieved for the worst environmental load cases. Fig.: 5-4 shows the temperature distribution for the hot case. The maximum gradient of 4 °C has be evaluated for the elevation bearing.

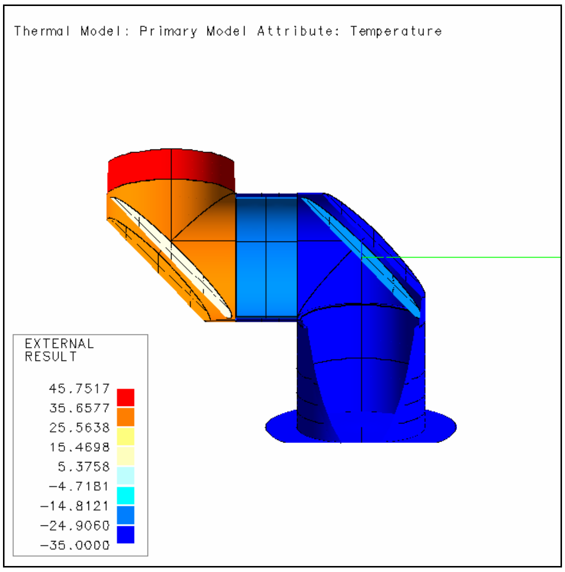

Fig.: 5-5 Temperature distribution in Hot Case (cold FUS I/F)

The temperature distribution in the cold case is shown in Fig.: 5-6 , the max gradient of 4,5 °C has been evaluated for the azimuth bearing.

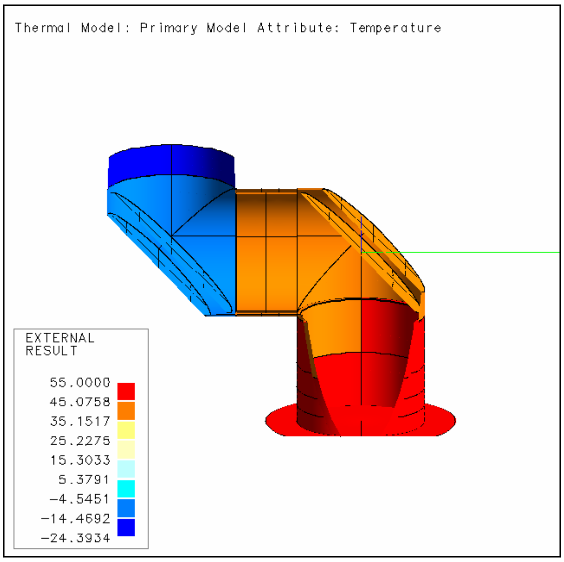

Fig.: 5-6 Temperature distribution in Cold Case (hot FUS I/F)

Cable Wrap

In order to guide the harnesses coming from the Elevation Drive to the Connectors located at the FUS, a slip ring or a cable wrap becomes necessary. The limited angle requirement and the reliability and lifetime requirements provide advantage to the cable wrap solution. The cable wrap will be procured at Mecanex.

5.3.2 Mirror Units

The CPA mirrors have been designed and analysed by Astrium, and will be produced by Carl Zeiss.
To come to a mirror design which fulfils the RMS requirements of < 10nm under all required boundaries was one of the most challenging tasks during the design phase. For the attachment to the CPA structure an intermediate plate with a mirror interface attached at 3 locations via isostatic mounts, has been designed. The intermediate plate is connected to the structural housing of the CPA via 3 adjustable screws to allow the alignment of the mirror without deflecting the isostatic mounts. Furthermore degradation of the RMS value due to integration errors between intermediate plate, isostatic mounts and mirror can be compensated by the surface finish applied only in the already pre-integrated configuration as shown in Fig.: 5-7.

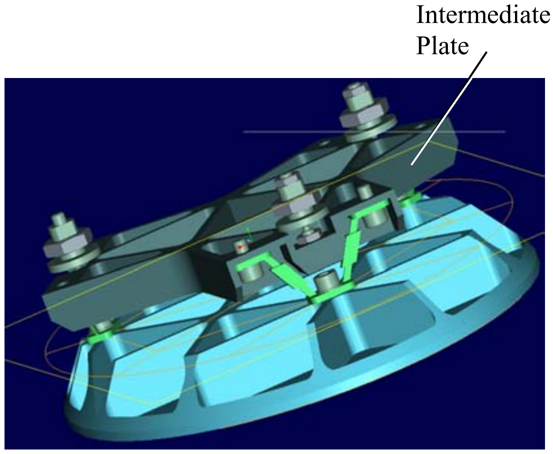

Fig.: 5-7 CPA Mirror

The design as shown in Fig.: 5-7 has been analysed by a FE-Model in order to get the portion of the overall RMS surface error which should be below 12 nm. In a first run where the mounting interface inside the mirror (SIC-mirror, structural glue, Invar insert, titan screw) has not been considered, the RMS deformation caused by bending moments of the isostatic mounts due to thermal gradients has been analysed with 10 nm well inside the tolerance. However detailed analysis of the attachment interface at the mirror backside, as shown in Fig.: 5-8 showed unexpected high deformation. A deformation plot is shown in Fig.: 5-9.

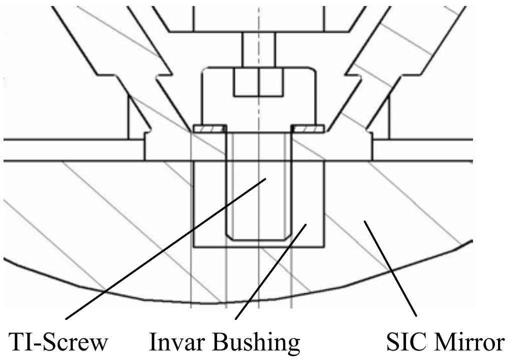

Fig.: 5-8 Mirror Attachment Interface (Invar Bushing)

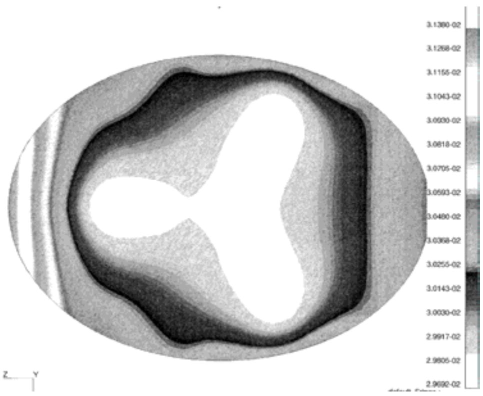

Fig.: 5-9 RMS error caused by Mirror Attachment Interface with Invar bushing

The major portion of the high deformation at extreme temperatures +84 °C to - 73 °C resulted from the combination of materials with different CTE inside the mirror back (CTE Titan 8,5 ppm/°C, Invar 1,5 ppm/°C and SIC 2,1 ppm/°C). Even using Invar screws the RMS error was far out of specification. A design improvement as shown in Fig.: 3-1solved the problem. Here the studs integral to the SiC mirror are used to avoid stresses in the mirror itself due to thermal mismatch of glue and surrounding metallic parts.

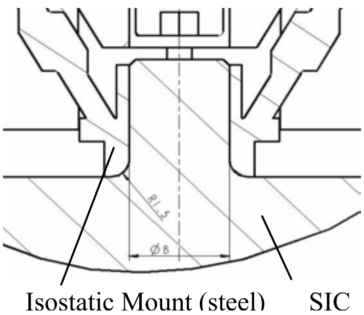

Fig.: 5-10 Improved Attachment Interface between Mirror and Isostatic Mount

Analysis of the improved interface between SIC Mirror an Isostatic Mounts showed good results. The RMS error is shown in Fig. 5-11

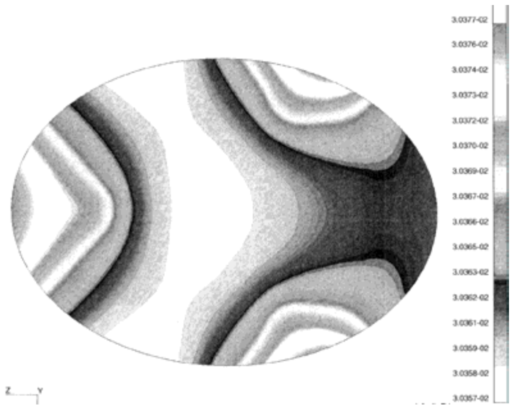

Fig.: 5-11 RMS error caused by Mirror Attachment Interface with integrated SIC bolt

5.3.3 Structural Parts

The driving requirements for all structural parts of the Drive Unit as well as of the Azimuth and Elevation Housing is high stiffness at low mass at good thermal match. The selected material for the Drive Unit housing as well as for the Azimuth and Elevation housing is DISPAL S225. This material has good thermal conductivity and a CTE very similar to steel allowing to keep the deformations due to gradients small. The light-tightness requirement can be met by closed structural elements with milled ribs for mass reduction.

5.3.4 Park Position Assembly (PPA)

The PPA consists of a ring-shaped housing which supports the calibration mirror by three isostatic mounts. The PPA housing is mounted to the Frame Unit. The alignment of the mirror can be performed relative to the PPA housing via 3 screws in a defined range without shims by pre-stressed spring elements. The PPA is totally de-coupled from the adjacent LLD.

5.3.5 Launch Locking Device

In launch configuration, when the LLD is locked, the Baffle is pressed to the PPA ring I/F via a rubber sealing to avoid that particles can come inside the CPA and contaminate the mirror. After release of the LLD, the CPA can be moved out of its parking position wither by commanding azimuth or elevation.

The LLD is positioned close to the PPA and consists of a stiff bracket with a mounting I/F to the Frame Unit, and a counterpart which is an integral part of the Baffle Fig.: 5-12. Prior launch, the LLD will be closed (locked) by tensioning the bolt of the "Frangibolt-Actuator" (memory-alloy). A conical hook positioned in the same plane will be clamped at the outer rim Baffle rim. Together with the separation I/F this hook I/F defines a stiff horizontal basis to withstand bending moments about elevation/azimuth.
For the release of the CPA, the actuator has to be activated for about 40 sec (80 Watts/24V). The hollow cylinder of the actuator extends the bolt to its rated break point until the bolt breaks.

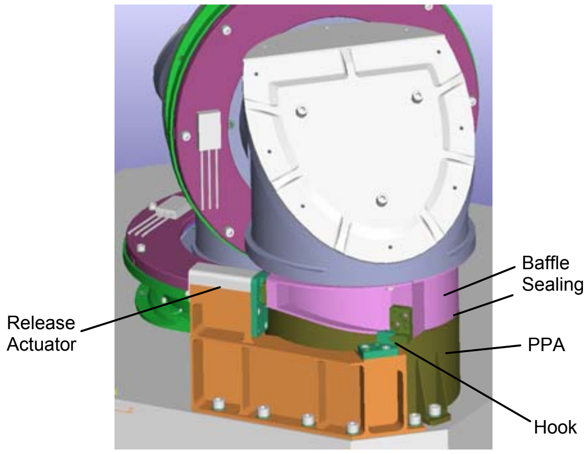

Fig.: 5-12 Arrangement of LLD Actuator

6 FINE POINTING ASSEMBLY (FPA) DESIGN

6.1 Design Requirements

In the following the major Design Requirements for the FPA have been listed. The requirements are all valid under varying I/F temperatures at the FUS of - 35°C to +55°C.

- Physical Properties

Mechanism Dimensions	43 x 43 x 31,5 mm
Overall Dimensions	63 x 53 x31,5 mm
Mirror Diameter:	36 mm
Mass:	250 gramm
Range:	+/- 3 deg

- Performance Data

Closed Loop Bandwidth:	> 4000 Hz
Accuracy:	< 15 µrad

6.2 Design Approach

The FPA is designed as a stiff and light weight construction used to guide an incoming Laser-Beam as well as an outgoing Laser Beam to the telescope and CPU. The beams are to be reflected by a high precision mirror.
The design of the FPA is driven by the following aspects:

- No friction producing elements - low resistive torque
- Mirror rotation axes max. 10 mm below the optical surface
- Mirror turning point in centre of gravity (COR = GOG)
- Spherical "linear" motors (high efficiency, linearity due to constant air gap)
- Kardanic Suspension via "TELDIX" pivot elements
- Design optimised for easy integration, adjustment, and exchange of electrical components
- High stiffness / low mass
- Minimisation of moving masses

6.3 Design Description

The mechanism consists of a Rotor (Mirror and Magnets) which is gimballed by 4 single flex pivots (Teldix-Pivots) and a Stator which is basically a plate with 4 Stator Brackets carrying the motor coils and a housing with mounting interfaces (see Fig.: 6-1).

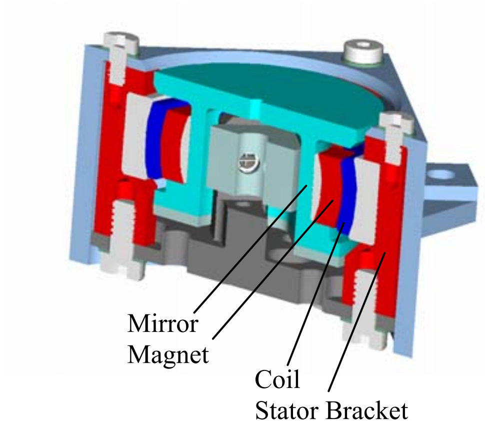

Fig.: 6-1 Diagonal cut through the FPA

In order to achieve maximum. electrical efficiency and high linearity, special spherical customised motors have been developed. The FPA will be operated in closed loop, the position feed-back is given by 4 capacitive sensors.

The fully integrated FPA is shown in Fig.: 6-2.

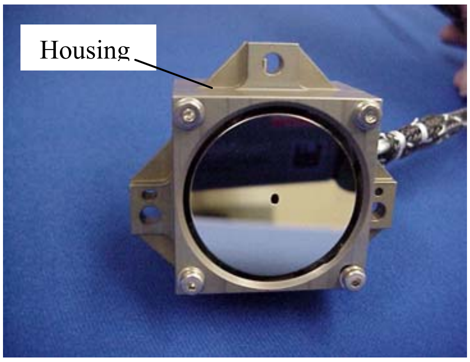

Fig.: 6-2 Integrated FPA

6.4 Description of Major FPA Components

6.4.1 Baseplate/Housing

The driving factors for the structural parts of the FPA (the Housing and the Baseplate), were to achieve a high stiffness and low mass. This was realised by a design comprising only two integral parts taking over structural and I/F tasks. The Housing includes all mechanical outer interface and provides the structural support for the motor brackets. Furthermore the Housing seals motors and sensors against dust and HF-disturbances.
The Baseplate provides the mounting I/F of the mirror axis and of the Motor Brackets. The Baseplate also includes the interfaces for the Sensors and the End Stops.
The selected material of all structural parts of the FPA is DISPAL S225 which has sufficient stiffness, high thermal conductivity and similar thermal expansion as the AlBe-Met mirror.

6.4.2 Drives

In order to achieve a high linearity over the required range of +/- 3 deg and to optimise the electromechanical efficiency, special customised spherical motors have been developed. The drives have been verified by extensive development tests in the scope of the pre-development phase and found suitable without any design modifications for transfer to a flight model.

6.4.3 Sensors

The built-in sensors of the FPA TV model were eddy-current sensors by Kaman. These sensors have been selected because of high resolution and low noise within acceptable size. The sensor systems (4 sensors per unit) and the drive electronics will be calibrated for the specific ranges and sensitivity of FPA and PAA.

6.4.4 Mirror

As a FPA mirror substrate AlBeMet was selected on basis of its high stiffness at low weight and good thermal conductivity. After manufacturing of the blank, the blank has been coated with Ni, thermal cycled and polished. The surface finish is driven by the optical requirements and is realised as a thin silver coating additionally protected against corrosion.

7 LESSONS LEARNT

Programmatic Issue: Prior to selection of standard of the shelf components it has to be clarified whether the supplier will support development and verification of the component for space application. Since materials lists were not provided by the manufacturer of the industrial encoder, verification of e.g. radiation tolerance would have become extremely difficult and expensive, even in case the encoder would have successfully passed the environmental tests.

The mirror support design is extremely critical in view of WFE (optical) performance. Only a very detailed FE model of the mirror showed the significant influence of temperature changes in gluing gaps and between mating materials on the optical performance.

The large bearings included into the design are very sensitive against thermal gradients even in case that matching materials are used. Therefore a high effort has to be spent to optimise the design for thermal requirements.

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