

Magnetic Bearing based cryo-mechanisms for future IR missions

T.C. van den Dool^a, F. Kamphues^a, W.L.M. Gielesen^a, B.C. Braam^{*a}
^aTNO Science & Industry, Stieltjesweg 1, 2628 CK, Delft, The Netherlands

ABSTRACT

TNO has developed a compact BreadBoard (BB) cryogenic Optical Delay Line (ODL) for use in future space interferometry missions such as ESA's Darwin and NASA's TPF-I. The breadboard delay line is representative of a flight mechanism. The optical design is a two-mirror cat's-eye. A linear guiding system based on magnetic bearings provides frictionless and wear free operation with zero hysteresis. The delay line has a voice coil actuator for single stage Optical Path Difference (OPD) control. The verification program, including functional testing at 40 K, has been completed successfully. The ODL design is at TRL 6.

TNO is currently developing an FTS Scan Mechanism for SPICA-SAFARI, based on the same design principles. The FTS Scan Mechanism will have a mechanical stroke of 35 mm and operates at 6 K. TNO intends to achieve TRL 4 by the end of 2009 and TRL 6 before the start of Phase B in 2011.

Other foreseen derivatives of the ODL are the delay lines for the far InfraRed missions SPIRIT and SAFIR of NASA and FIRI of ESA.

Keywords: optical delay line, ODL, cryogenic, DARWIN, TPF-I, SPICA, SAFARI, FTS scan mechanism, active magnetic bearings, nano-positioning, aperture synthesis, nulling interferometry.

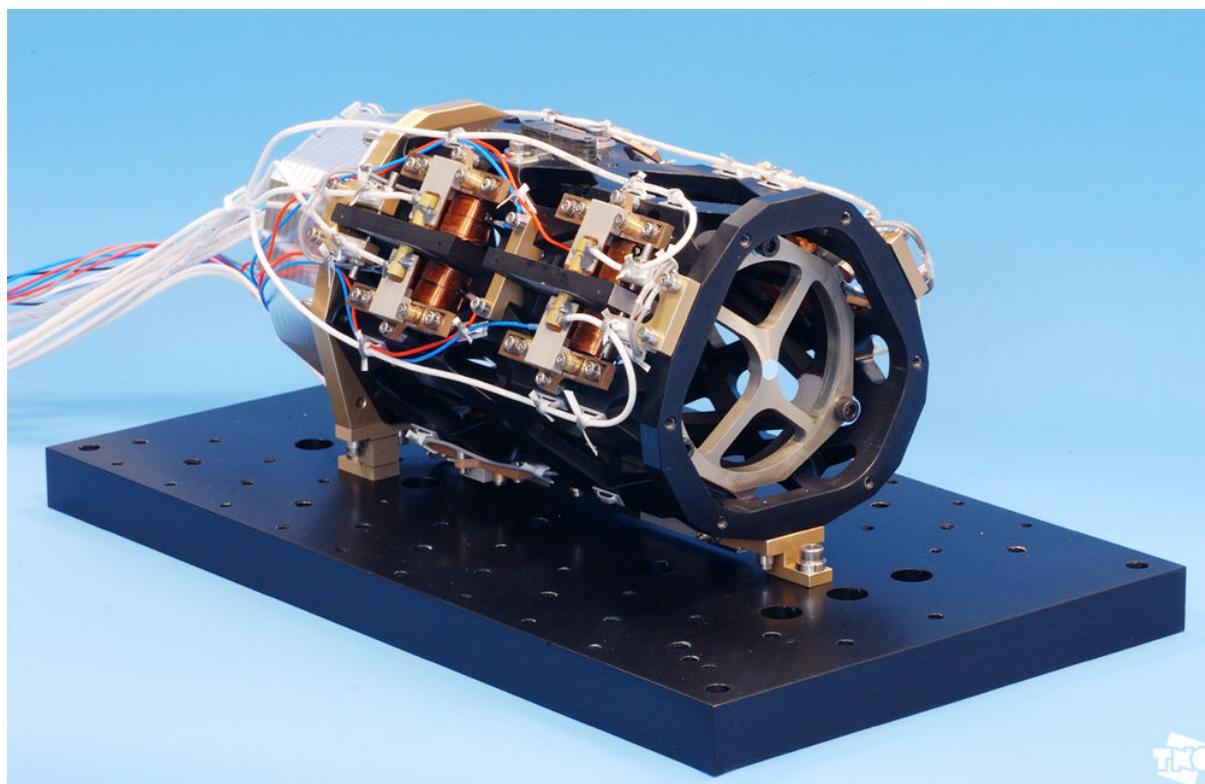


Fig. 1. The Darwin BB Optical Delay Line

* ben.braam@tno.nl; phone +31(0)152692180; fax +31(0)152692111; www.tno.nl

1. INTRODUCTION

1.1 Darwin BB ODL

TNO has developed a compact BreadBoard (BB) cryogenic Optical Delay Line (ODL) for use in future space interferometry missions such as ESA's Darwin [1] and NASA's TPF-I.

The design, implementation, and testing of these optical delay lines by TNO (see Figure 1) are described in this paper. Within the Darwin ODL BB project, the responsibilities were divided as follows:

- TNO: project management, systems engineering, optical design, OPD control, and integration
- Micromega-Dynamics: magnetic bearing guiding system development
- SRON: actuator and power amplifier development and cryogenic consultancy
- Centre Spatiale de Liege (CSL): coating engineering and 40K TV facility
- Dutch Space: thermal modeling and development tests at 100 K
- Alcatel Alenia Space: mission level consultancy and verification tests (with Sageis-CSO)

The design of the delay line started in December 2003 [2]. The BB delay line was built in the second half of 2004. The manufacturing and assembly phase was followed by a comprehensive engineering test program in 2005, including functional testing at 100 K. Verification testing, including performance measurements at 40 K, was carried out in the first half of 2006. The project was completed with a final presentation at ESTEC on 12 December 2006. The ODL design is at TRL 6.

1.2 SAFARI FTS Scan Mechanism

The Space Infrared Telescope for Cosmology and Astrophysics (SPICA) is a 3.5-meter telescope actively cooled to below 5 K. The Japanese Aerospace Exploration Agency (JAXA) plans to launch SPICA into an Earth-Sun Lagrangian-point L2 orbit in 2017. The proposed European instrument contribution to SPICA is the Spectrometer for Astronomy in the Far Infrared (SAFARI). The SAFARI Phase A instrument study is done by a European consortium led by Rutherford Appleton Laboratory (RAL) in the UK [6]. SAFARI will perform high sensitivity imaging spectroscopy in the 35-210 μm band.

TNO is currently developing an FTS Scan Mechanism for SPICA-SAFARI, based on the Darwin ODL design principles. The FTS Scan Mechanism will have a mechanical stroke of 35 mm and operates at 6 K. TNO intends to achieve TRL 4 by the end of 2009 and TRL 6 before the start of Phase B in 2011. Within this study TNO works closely together with RAL and former ODL partners Micromega-Dynamics and SRON:

- TNO: project management, systems engineering, optical design, OPD control
- Micromega-Dynamics: magnetic bearing guiding system development
- SRON: actuator and power amplifier development and cryogenic consultancy

1.3 Other missions

Other foreseen derivatives of the ODL are the delay lines for the far InfraRed missions SPIRIT and SAFIR of NASA and FIRI of ESA. References to the TNO ODL can be found in the SPIRIT and SAFIR white papers.

2. DARWIN ODL

2.1 Design Description

The main requirements for the Darwin ODL are [3]:

- Optical beam diameter: > 25 mm
- OPD stroke: 20 mm (10 mm mechanical)
- Dimensions: < 300 x 100 x 100 mm³
- Mass: < 10 kg (target: < 6 kg)
- Space vibrations: 100nm rms (-40 dB/dec for $f > 1$ Hz)
- OPD stability: < 1 nm RMS (0.5 nm mechanical)
- Dynamic response: 25 μ m step in < 20 ms.
- Overall power dissipation: < 2.5 W
- Power dissipation in ODL: < 25 mW
- Output beam tilt: < 0.24 μ rad
- Output beam lateral shift: < 100 μ m
- Wavelength range: 0.45 - 20 μ m
- Wavefront distortion: < 63 nm rms
- Relative spectral response: < 10e-4
- Chromatic phase differences: < 0.1 nm rms
- Relative polarization Rotation: < 0.1 deg
- Relative polarization Ellipticity: < 0.1 deg
- Transmission: >94% (4 to 20 μ m wavelength)
- Operational temperature: 40K
- Ambient pressure: 10e-6 mbar
- Quasi static design load: +/-45 g
- Random vibration levels: 30 g RMS
- Shock: 200 g
- Design lifetime: 10 years

The basic structure of the ODL is arranged around a cat's-eye with a focal length of 120 mm, which is determined by optimizing between overall size of the ODL and sensitivity to alignment and guiding errors (see Figure 2). Maintaining polarization of the incoming beams is easier with a cat's-eye than for instance with a corner cube. The use of a cat's-eye would also enable optional pupil imaging (currently not a requirement). However, the ODL design does not exclude the future use of a corner cube.

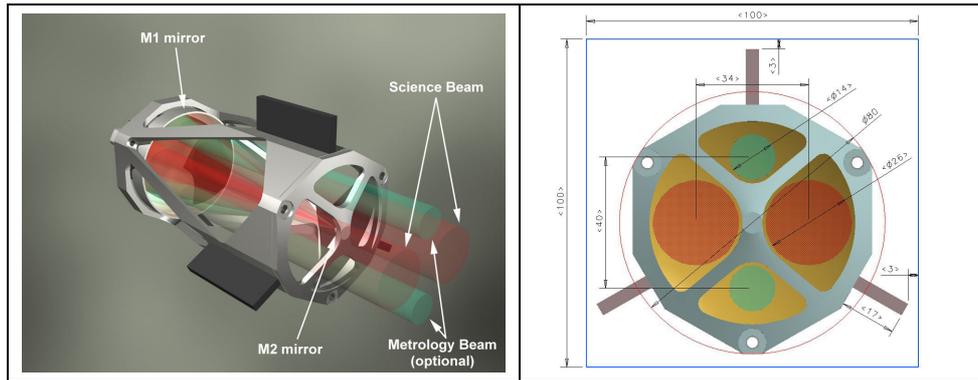


Fig. 2. LEFT: the optical design of the ODL is a cat's-eye with a primary 63 mm parabolic mirror (M1) and a small 6 mm secondary mirror (M2). RIGHT: front view of the ODL with 25 mm science beam entrance and exit and 14 mm metrology beam (optional).

All parts of the main structure are manufactured out of a single piece of 6061-T6 aluminum to reduce thermal expansion differences when cooling down to the operational temperature of 40 K. The mirrors are Alumiplate[®] to reduce surface roughness after diamond turning (see Figure 3). The use of Alumiplate prevents bimetallic bending of the mirrors at cryogenic temperatures. The design of the cat's eye is fully athermal. Both mirrors are gold coated to obtain the required reflectivity in the mid infrared.



Fig. 3. Inspection of the parabolic M1 mirror. The mirror is made of 6061-T6 Aluminum, Alumiplate[®], diamond turned, and gold coated. The M1 mirror support is a so called "wine-glass" type.

A single stage OPD actuation scheme has been selected, which results in relatively low overall complexity. The power dissipation of a single stage is very low (< 1 mW at 40 K) and provides the best optical performance (no focus errors of the cat's-eye due to a piezo actuated secondary mirror).

Magnetic Bearings (MBs) based on reluctance type electromagnets are used for the linear guiding mechanism (see Figure 4). The development was carried out by Micromega-Dynamics and based on their experience in the MABE project [4]. MBs have no friction, no wear, require no lubrication and are simpler and more compact than flexures. Flexures would also result in parasitic forces that complicate control and/or increase power consumption. The MB design is double redundant; each yoke has 2 coils and each coil consists of 2 separate windings. Five MB sets have been implemented but provisions have been added for a 6th MB coil set for extra redundancy.

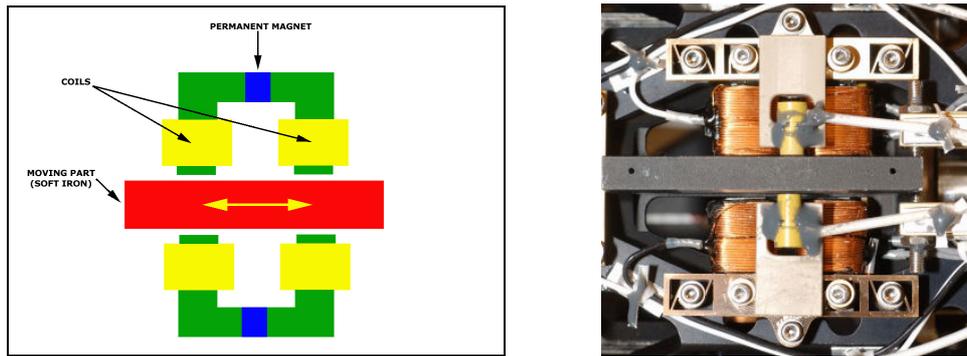


Fig. 4. Magnetic bearing design; LEFT: a soft iron moving target (horizontal bar) is retained in a non-stable equilibrium by 2 yokes (horse-shoes) with attracting permanent magnets (top and bottom). Four coils (squares around the horse-shoes) and an appropriate controller with eddy current sensors actively control the centre position. Five sets of bearings are used in the ODL to constrain five degrees of freedom. RIGHT: Close-up photograph of 2 integrated magnetic bearing assemblies.

For OPD actuation a fully redundant 2-coil Lorentz force motor is implemented (see Figure 5 left). The design of this actuator is based on proven hardware, used for the ISO and HIFI missions (both for a cryogenic environment). This voice-coil actuator is mounted on the backside of the parabolic M1 mirror through flexures such that thermal expansion differences do not influence the shape of the M1 mirror (see Figure 5 right). An ultra low noise current amplifier with a large dynamic range powers the voice coil.

The flight model of the ODL will need a launch lock. A launch lock was not part of the development program, but a simple manual lock for transport has been implemented. Otherwise the ODL has been fitted with all necessary provisions for a launch lock, such as a 1200 N isostatic mount with 3 ball-grooves at the M2 side of the rotor.

The ODL dynamic MB is equipped with a 1-g magnetic off-loading device, to enable ground testing in horizontal position. In future a retraction mechanism will be required for it; this has not been implemented in the breadboard ODL. It is also possible to enlarge the MBs somewhat so that they can lift the mass of the rotor without the need for a separate magnet. At 40 K the MB power dissipation is very low anyway.

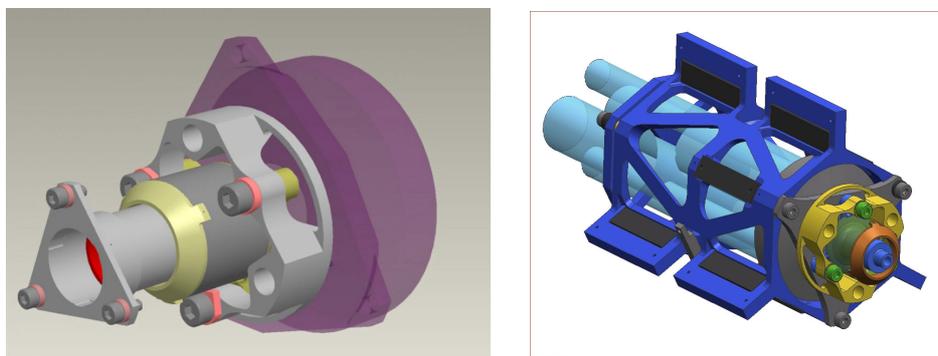


Fig. 5. LEFT: CAD model of the OPD voice coil actuator. RIGHT: Rotor (moving part) design with parabolic mirror at the back. The magnet of the voice-coil actuator is mounted on top of it through the flexure interface. The rotor has 6 flaps (4 visible) with soft iron magnetic bearing targets (black). The science and metrology beams are shown in transparent light blue.

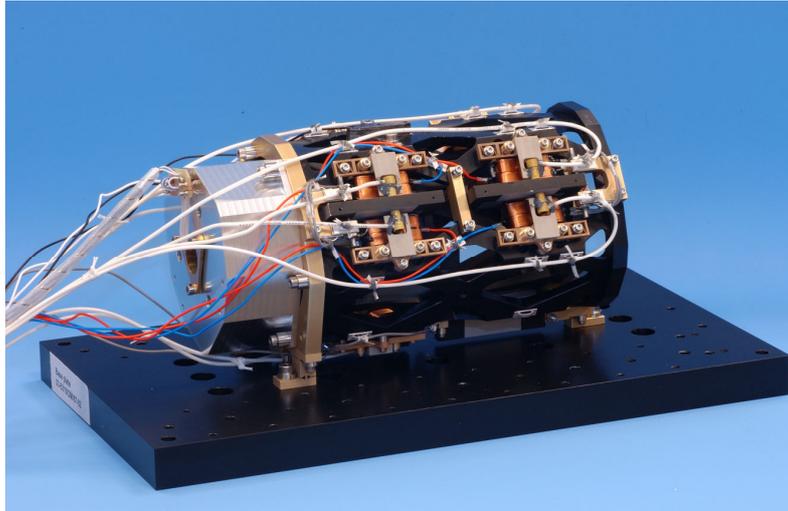


Fig. 6. Complete ODL design with the rotor (moving part) inside the stator. The voice-coil is mounted on a separate cap on the back-side (shown on the left).

The control of the magnetic bearings and the OPD was implemented on a real-time Linux system with mostly commercially available components. The system was programmed from Simulink and can be operated with either Matlab or Labview user interfaces. For a future flight program it was verified that the control could be implemented in a low-power (< 2.5 Watt) FPGA system. A breadboard low power FPGA controller has been developed with SRON in a NIVR sponsored program.

The OPD control is based on loop-shaping techniques. This proved to be sufficient to obtain the required sub-nanometer OPD stability, even in an earth environment with 10 fold higher environmental vibration levels than expected in a future Darwin mission. If needed, further improvement or robustness against changes can be obtained with adaptive control [5].

The OPD sensor (Fringe Sensor in DARWIN) was simulated by an Agilent laser metrology system with sub-nanometer resolution (0.3 nm) and a 10 kHz sampling rate. This has the advantage that a large range of control bandwidths could be tested, e.g. to cope with a much higher disturbance spectrum during ground testing. A typical test setup is shown in figure 7.

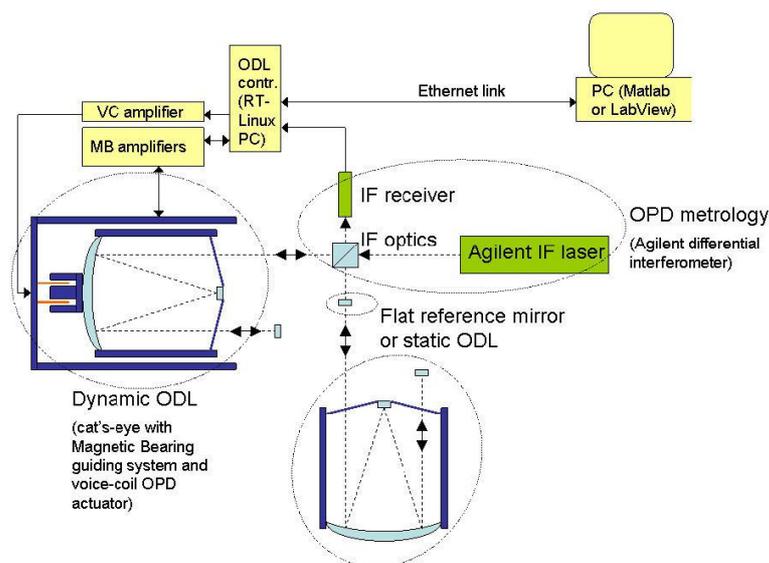


Fig. 7. Example of an ODL breadboard test set-up.

2.2 VERIFICATION PROGRAM

A comprehensive development test program was carried out by TNO and SRON in 2005, preceding the verification phase. The development test program included deep thermal cycling of components and assemblies and operation of the ODL at 100 K in vacuum at Dutch Space. OPD control algorithms were extensively tested under ambient conditions.

Verification of the optical coating requirements of the mirrors was mainly done at sample level at ambient temperature by CSL. The coating tests included the following measurements:

- Mirror surface roughness
- Coating adhesion before and after thermal cycling
- Optical transmission
- Relative spectral response and chromatic phase differences
- Relative polarization rotation and ellipticity

Alcatel Alenia Space, in co-operation with Sageis-CSO, carried out the verification test program of the assembled ODL. It comprised an ambient test program and cryogenic test programs at 120 K and 40 K. After completion of the ambient test program, the 120 K and 40 K test programs were prepared and carried out at Dutch Space (Leiden, the Netherlands) and in the Focal 2 facility at the Centre Spatial de Liège (CSL, Belgium, figure 8).

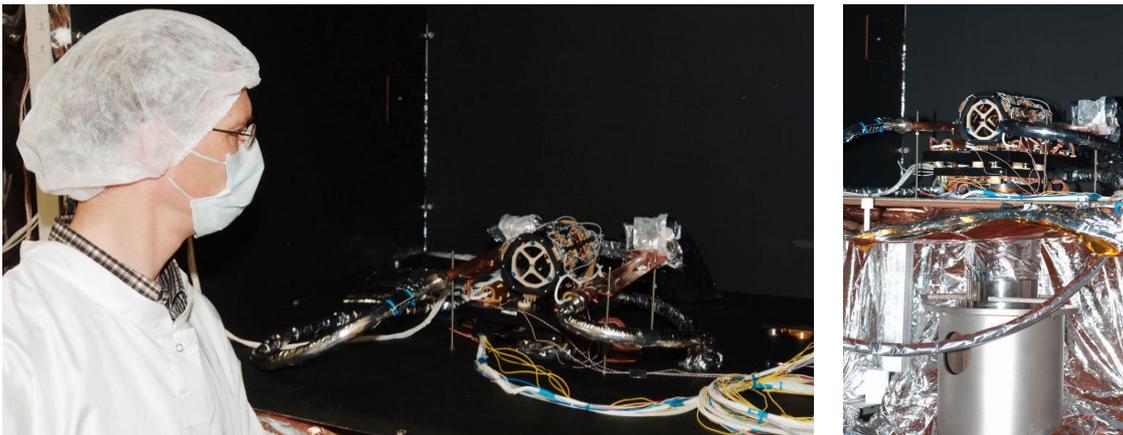


Fig. 8. Verification test setup in CSL's Focal-2 thermal-vacuum facility in Liege, Belgium.

2.3 Performance

The OPD stability during the 40 K TV test at CSL was between 5 and 10 nm rms (see Figure 15). This is higher than the stability reached during the integration phase in the TNO laboratories (0.9 nm rms), due to the higher disturbance spectrum of the TV facility (~10x higher than in the TNO laboratory at high frequencies between 50 Hz and 500 Hz).

Based on these measurements, it has been calculated that an OPD error of better than 1 nm can be achieved in the presumed Darwin spacecraft vibration environment, when the fringe sensor sample rate is higher than 100 Hz. The sampling frequency during the verification program was 10 kHz.

At 40 K the total power dissipation in the breadboard ODL was around 20 mW, mainly as the result of heat leak through the cabling. For reasons of cost reduction, no special cryogenic harness was used for the Bread Board model. For the flight model, special cryogenic cabling will be used, which will reduce the power dissipation through the cables to approximately 2 mW and this will dominate the total power dissipation. The power dissipation in the magnetic bearings at 40 K was measured to be 0.5 mW. This was due to the very low resistivity of the low oxygen copper wire used. The power dissipation in the MB coils is very low because they are

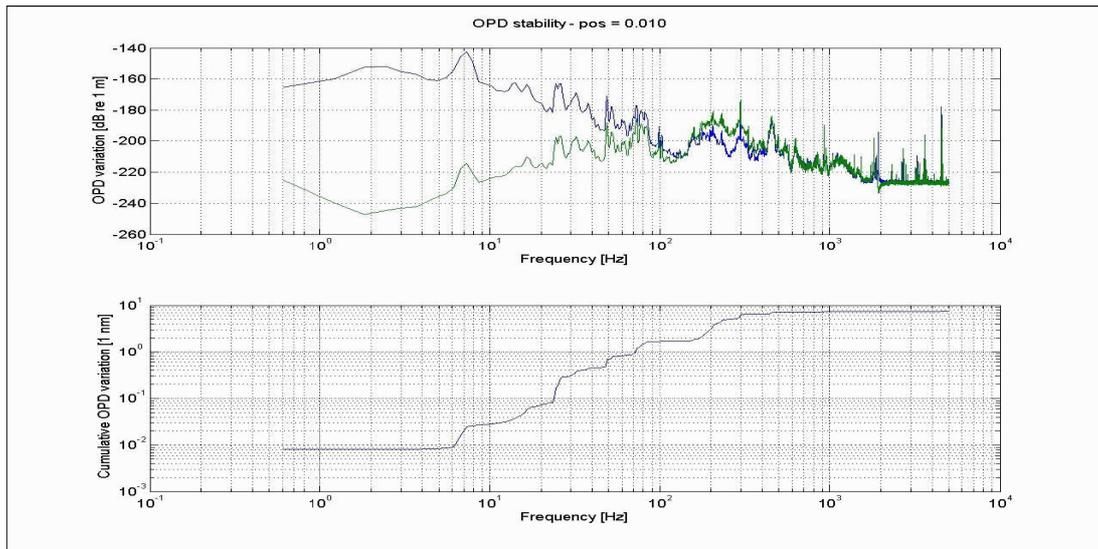


Fig. 9. Open and closed loop OPD stability PSD (upper plot) and cumulative PSD (lower plot) during the 40 K TV test (-180 dB = 1 nm²/Hz, -200 dB = 0.01 nm²/Hz, etc.).

To further verify the beam tilt stability, the tilt of the rotor was measured (see Figure 10). It proved to be in the order of 40 μ rad, far better than the 400 μ rad that it was designed for. The effect on the beam after going through the cat's-eye was deduced from this figure to be far lower than the required 0.05 arcsec. It was also verified that the rotor tilt could be further reduced to 0.5 μ rad with a lookup table for the magnetic bearing steering.

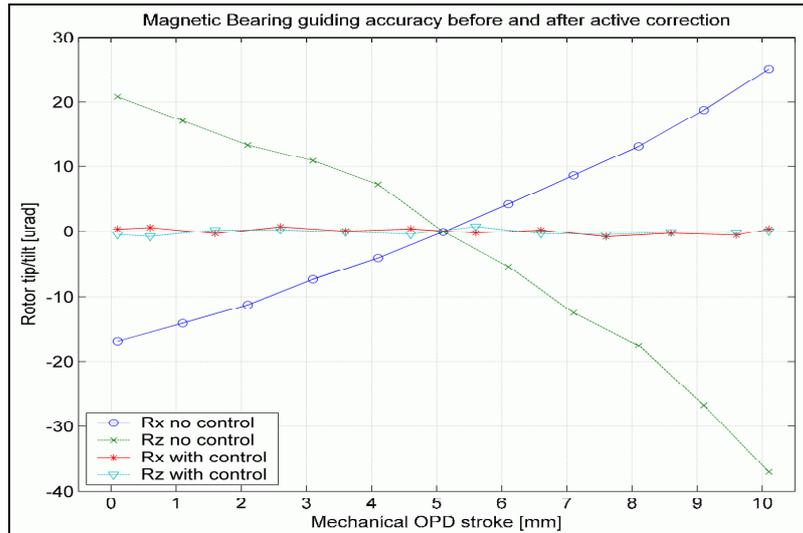


Fig. 10. Dynamic rotor tilt before and after active compensation with the magnetic bearings.

The verification test program included Wave Front Error (WFE) measurements at ambient temperature, at 120 K and at 40 K and for 3 field of view angles (0 and ± 3 arcmin). The final WFE at ambient was better than approximately 20 nm = $\lambda/30$ rms for a beam diameter of 17 mm and all field of view angles.

At cryogenic temperatures the WFE was somewhat larger than $\lambda/20$ due to residual differential thermal contraction. This was corrected by adjusting the distance between the M1 and M2 mirrors. The WFE does not depend on the OPD position of the ODL.

3. SPICA-SAFARI FTS SCAN MECHANISM

SPICA is a candidate for the ESA Cosmic Vision programme and sufficient TRL will have to be demonstrated before September 2009, to ensure a favorable decision for the SPICA mission.

SAFARI asks for a compact and lightweight mechanism with high scanning velocity and small position error. The operational temperature will be 6 K and power dissipation shall be below 1 mW. SAFARI will also require a low power internal cryogenic position sensor (since there is no Fringe Sensor like in Darwin). In addition SAFARI needs a re-usable lock for certain observation modes. These are all significant deviations from the Darwin design and will require partly new technology as well. During a technology review in 2008, ESA has recommended to use the Darwin ODL technology for the SAFARI FTS scan mechanism. TNO is currently developing an FTS Scan Mechanism for SPICA-SAFARI, based on magnetic bearings. The FTS Scan Mechanism will have a mechanical stroke of 35 mm and operates at 6 K. The use of magnetic bearings will result in a much compact mechanism with smaller dimensions and mass compared to flexure based mechanisms. Due to the zero friction and hysteresis of the magnetic bearings, the performance of the mechanism will exceed that of similar flexure based mechanisms. A comparison of the SAFARI FTS Scan Mechanism requirements and the Darwin ODL performance is given in table 1.

	FTS Requirement (*)	ODL Requirement	ODL Measured
Beam diameter	30 mm ?	25 mm	27 mm
Linear stroke	35 mm	> 20 mm	20.2 mm
FTS Mirrors location accuracy	< 15 nm [TBC]	< 0.5 nm	< 0.5 nm (RMS on earth)
FTS Mirrors location resolution	< 5 nm	-	< 0.1 nm
FTS mirrors velocity	30-500 (step 1) $\mu\text{m/s}$	> 250 $\mu\text{m/s}$	0-10000 (step <0.1) $\mu\text{m/s}$
Speed stability	< 2 $\mu\text{m/s}$ @ 0-20Hz	-	<< 1 $\mu\text{m/s}$ (< 0.5 nm RMS)
FTS Mirror accel-/deceleration	within 0.5 mm	-	within 0.005 mm
Minimum step	< 750 nm	< 0.5 nm	< 0.1 nm
Settling time	< 200 ms [TBC]	< 20 ms	< 20 ms
FTS mirror rotation (tip/tilt)	< +/-30 arcsec	-	< 5 arcsec (<0.5 optionally)
FTS mirror lateral displacement	< 100 μm	< 50 μm	< 1 μm
Scans	150000 in flight	-	Unlimited
Magnetic field emissions	TBW	-	~ 50 μT @ 10 cm
Stray light emissions	TBW	<10 ⁻⁷ @ $\lambda=4$ nm.	Not verified
Operational temperature	4 K	40 K	tested at 25 K
Peak dissipation	< 1 mW at 6 K (TBC)	< 25 mW	< 1 mW
Parasitic heat load	< 300 μW	-	TBD
Dimensions	TBD	<100x100x300 mm ³	114 x 116 x 210 mm ³ (no LL)
Mass	< 3 kg	< 10 kg	< 1.7 kg

(*) Courtesy of Rutherford Appleton Laboratory (RAL)

Table 1 comparison of SAFARI FTS Scan Mechanism requirements and Darwin ODL performance

The SAFARI FTS Scan Mechanism will require considerable development, including some new technologies, like an ultra low power position sensor. TNO has identified a number of development areas:

- Optimization of optical layout and iteration with the instrument design
- Launch Lock (a conceptual design study has already been carried out and an isostatic LL mount was implemented)
- Internal metrology sensor (e.g. ultra low power fiber interferometer)
- Behavior of magnetic and soft iron material (literature study)
- Cryogenic harness (first assessment shows that requirement is feasible)
- Design for failure tolerance / redundancy
- Implement “safe mode” (for instance combine with launch lock)
- Design for testing on earth (operation at 1g; by increasing MB coil size) and zero-g behavior (e.g. influence on alignment and power dissipation)
- Low-power flight-electronics (ODELCO a prototype FPGA based controller was designed by SRON, but not yet implemented).

The preliminary design of the SAFARI FTS Scan Mechanism consists of a dual-corner cube structure with a central voice coil actuator (figure 11). This configuration will be further optimized during a number of design iterations in close cooperation with RAL and SRON. A Launch Lock design will be implemented.

SAFARI FTS Scan Mechanism Darwin ODL based design sketch with corner cube optics

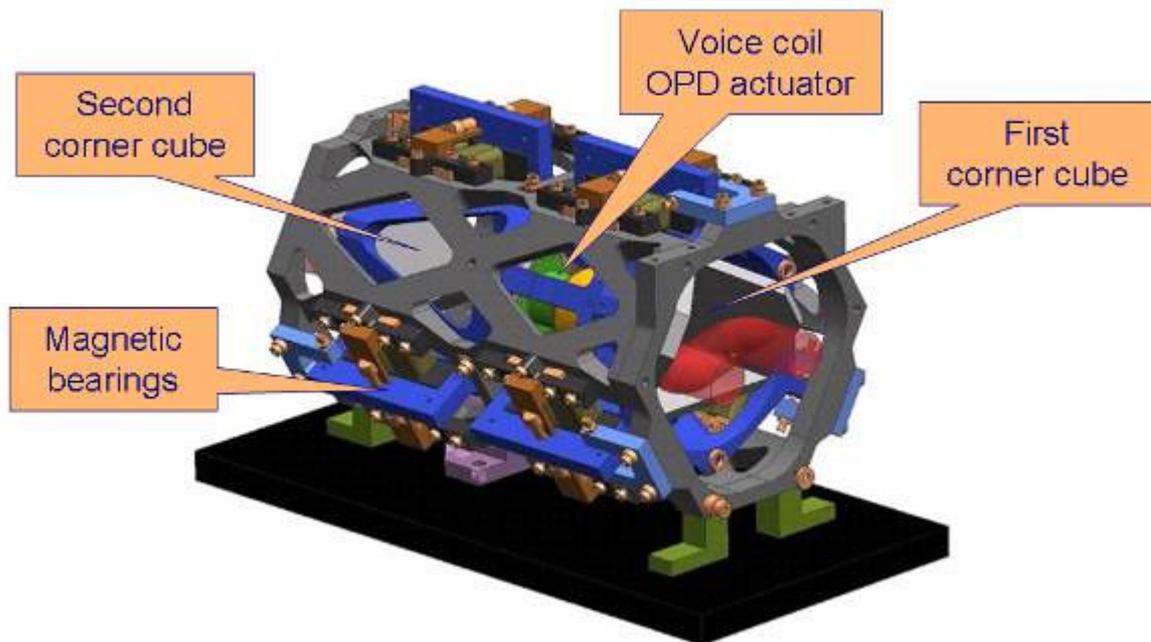


Figure 11 MB based FTS Scan Mechanism with two corner cubes

TNO intends to achieve TRL 4 by the end of 2009 and TRL 6 before the start of Phase B in 2011.

4. CONCLUSIONS

TNO and its partners have demonstrated that accurate optical path length control is possible with the use of magnetic bearings and a single stage actuation concept. Active magnetic bearings are contactless, have no friction or hysteresis, are wear free, and have a low power dissipation. In combination with a two-mirror cat's eye and a voice-coil actuator, the mechanism is also compact with a low mass. The design of the Darwin BB ODL meets the ESA requirements. The Darwin BB ODL is representative of a future flight mechanism, with all materials and processes used being suitable for flight qualification.

A similar mechanism is under development for the SPICA SAFARI FTS Scan Mechanism and will meet or exceed current SAFARI requirements.

5. ACKNOWLEDGEMENT

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REFERENCES

1. ESA-SciA, *DARWIN Mission Summary Status*, reference: SCI/AM/DARWIN-SUMSTAT/06, issue 2.0, rev.2, 19-2-2007.
2. T.C. van den Dool et al, *The design of a breadboard Cryogenic Optical Delay Line for DARWIN*, SPIE Conference Astronomical Telescopes and Instrumentation Vol. 5495-40, June 2004, Glasgow, United Kingdom.
3. *Statement of Work, Optical Delay Lines, Programme Reference: TRP, ID-OP-12 TOS-MMO/2002/276*, issue 2.0, 6 March 2003 and clarifications 1, 2 and 3.
4. *MABE, Fine Precision Mechanism Based on Magnetic Bearing Technology*, Micromega Dynamics – Executive Summary (ESA Contract No 13676/99/NL/PA)
5. N.J. Doelman, T.C. van den Dool, *Active Vibration Control for an Optical Delay Line*, Proc. of Active 2002, pp.887-898
6. *The European contribution to the SPICA mission*, Bruce Swinyard et al, SPIE 7010-17, SPIE Astronomical Telescopes and Instrumentation 2008, June 2008