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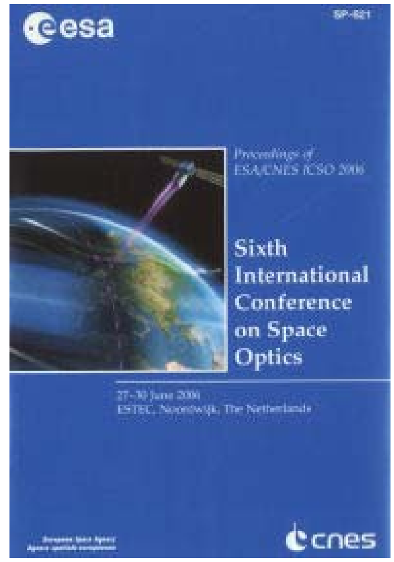

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THE DARWIN BREADBOARD CRYOGENIC OPTICAL DELAY LINE

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ABSTRACT

TNO, in cooperation with Micromega-Dynamics, SRON, Dutch Space and CSL, has designed a compact breadboard cryogenic delay line (figure 1) for use in future space interferometry missions. The work is performed under ESA contract 17.747/03 in preparation for the DARWIN mission. The breadboard (BB) delay line is representative of a flight mechanism. The delay line has a single stage voice coil actuator for Optical Path Difference (OPD) control, driving a two-mirror cat's eye. Magnetic bearings provide frictionless and wear free operation with zero-hysteresis. The design of the BB delay line has been completed.
The development test program, including operation at 100 K has been completed. The verification test programme is currently being carried out and will include functional testing at 40 K.

Keywords: optical delay line, ODL, cryogenic, DARWIN, TPF-I, active magnetic bearings, nanopositioning, aperture synthesis, nulling interferometry

1. INTRODUCTION

The DARWIN Optical Delay Line will play an important role in ESA's DARWIN Infrared Nulling Interferometer. The delay line has to equalise and fine-tune the optical path length differences between the telescopes in the interferometer constellation. The optical path lengths must be equalised at sub nanometre level without introducing significant wave front errors, beam tilt or lateral beam deviation. The delay lines will also be used for fringe scanning, after course acquisition of the telescope constellation. The delay lines will be placed on the optical bench in the Hub spacecraft and will operate at 40 K [2].

Within this study, the responsibilities for the design and development are divided as follows:

- TNO – Project management, systems engineering, optical design and OPD control
- Micromega-Dynamics – Guiding system development
- SRON – Actuator and power amplifier development and cryogenic consultancy
- CSL – Coating engineering and 40K TV facility
- Dutch Space – Thermal modelling and development tests at 100K

The verification test programme is carried out by Alcatel Alenia Space in cooperation with SAGEIS-CSO and will include functional testing at 40 K.

Fig. 1 - Darwin Breadboard Optical Delay Line

2. DESIGN DESCRIPTION

The delay line has a single stage voice coil actuator for Optical Path Difference (OPD) control, driving a two-mirror cat's eye. Magnetic bearings constrain the other five degrees of freedom and provide a frictionless and wear free guiding system [3]. The magnetic bearings use the same controller as the OPD control, eliminating the need for an additional control board. The smooth operation of the magnetic bearings, allow single stage OPD control, which contributes to a better optical quality of the cat's eye and reduced OPD control complexity. The entire mechanism is constructed from Aluminium 6061, with the exception of a few small components. All parts are constructed from the same material lot, to ensure highly isotropic behaviour. This makes the design fully athermal. Where components with a different CTE are employed, flexures are used to minimise thermal distortions.

2.1 Optical design

The delay line employs a two-mirror cat's eye. If pupil imaging is not required for DARWIN, a corner cube type retro reflector could also be used, still using the same magnetic bearing guiding technology.
The entire cat's eye (mirrors + structure) is manufactured from Aluminium 6061, which ensures athermal behaviour (which means that the focus is retained when cooling down to 40 K). Aluminium bolts are used to mount the mirrors to the structure, to further reduce preload variations (and possible focal errors).
The mirrors are plated with a 200 micron layer of Alumiplate ® and subsequently diamond turned (figure 2) at TNO to a surface roughness of around 2 nm RMS and a P-V Wave Front Error (WFE) of less than 60 nm over the full 61 mm aperture. The use of Alumiplate prevents bimetallic effects, which can cause differential thermal bending of the mirrors at cryogenic temperatures.

Fig. 2 - Diamond turning of M1 mirror

After WFE and surface roughness measurements, the mirrors were coated by CSL with a single layer of protective Gold. The coating properties of the mirrors were measured at CSL (optical characterisation, micro roughness, coating adhesion).

2.2 Guiding mechanism

The guiding mechanism is based on active magnetic bearings. The magnetic bearing system has been designed by Micromega-Dynamics, who has extensive experience with magnetic bearings, including for space mechanisms such as MABE [10].

Although relatively new for space applications, magnetic bearings offer a number of benefits over conventional guiding systems, such as ball bearings and flexures. The main advantages are:

- Zero friction and zero hysteresis
- No lubrication required
- Magnetic bearings are non-contact (air gap approximately 0.5 mm), and wear free.
- The inherent cleanliness makes them highly suitable for sensitive optical instruments.

In addition, the power dissipation is extremely low and mechanical alignment errors can be corrected with active bearing control.

The DARWIN BB ODL will have five magnetic bearings to constrain 5 degrees of freedom (the OPD controller constrains the other degree of freedom).

Figure 3 shows the magnetic bearing configuration. A piece of soft iron is positioned between two permanent magnets. The system is inherently unstable and a set of active coils is added for balancing. Eddy current sensors provide position information to the bearing controller. The permanent magnets (blue) are located in the centre of the soft iron yokes (green). The permanent magnets produce a constant magnetic flux and the coils generate a variable magnetic flux that is added (or subtracted) to (from) the constant one.

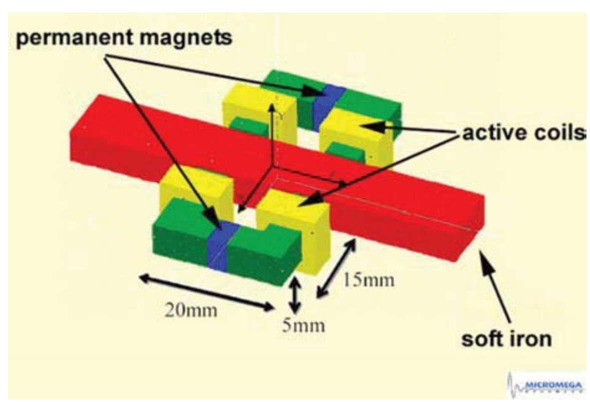

Fig. 3 - Active magnetic bearing

The bearing and sensors are fully redundant. The control is implemented on the same processor as used for OPD control.
The moving part of the magnetic bearing is an integral part of the cat's eye. Therefore both the static and moving part of the magnetic bearing were machined and wire cut from the same lot of material as the mirrors, to minimise CTE variations and guarantee the athermal behaviour of the cat's eye.
The magnetic bearing was assembled and tested at Micromega-Dynamics in Liege, Belgium. The position of the magnets was adjusted to ensure proper guiding accuracy and minimum power dissipation. The magnetic bearing is equipped with a 1-g magnetic off loading device, to enable ground testing in horizontal position. The measured power dissipation of the magnetic bearing in the centre position is less than 1 mW. Due to 1-g loading, and subsequent centre of gravity shifts, the power dissipation in the magnetic bearings at the extreme positions is ca. 20 mW at 40K. In 0-g condition the power dissipation will be less than 2 mW.

2.3 Actuation and OPD control

The actuator and power amplifier for Optical Path Difference (OPD) control has been developed by SRON. The design of the actuator is based on proven hardware used for the ISO and HIFI missions (both for a cryogenic environment).
The voice coil actuator is located at the back of the cat's eye. Since the actuator magnet is mounted on the back of the mirror, an intermediate flexure structure was developed, in order to minimize the thermal strains in the mirror caused by the different CTE's of magnet and mirror.
The coil is attached to the static part of the ODL and the magnet is attached to the moving part, thus preventing disturbance forces caused by electrical wires. For reasons of redundancy, the voice coil consists of two concentric coils, an inner and an outer one. The amplifier powering the voice coil is a very low noise current amplifier with a large dynamic range.

Fig. 4 - Voice coil assembly (magnet on the left, coil on the right)

The DARWIN BB ODL uses a digital controller. The controller has been implemented on a real-time Linux PC, to enable quick adjustment and fine-tuning of control parameters during the development phase. For the DARWIN mission, the control algorithm will be implemented in a low power digital processor. The control model is shown in figure 5.

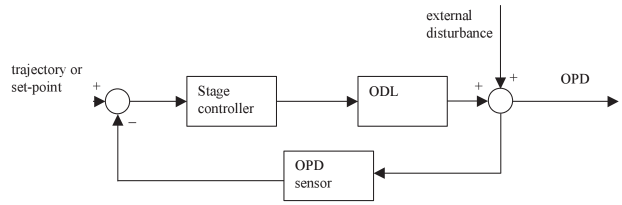

Fig. 5. OPD control model of single stage delay line

The OPD sensor (Fringe Sensor in DARWIN) is simulated by a laser metrology system with sub nanometre resolution. This has the advantage that a large range of control bandwidths can be tested, e.g. to cope with a much higher disturbance spectrum during ground testing. With the advanced control algorithms that have been developed by TNO during the past decennium, a rejection ratio of up to 1:3.000 can be achieved, thus enabling nanometre stability, even in an environment with high frequency disturbance.

In path stabilization mode, the control system needs to reject a stochastic-type disturbance by means of a feedback action (there is no advance information available). For this type of regulator system, fundamental limits on the performance apply. The maximum, theoretical achievable disturbance rejection depends on the spectral characteristics of the disturbance together with the total loop delay. Here, we have assumed that the plant dynamics – other than the delay - can be compensated for perfectly. In general, the maximum achievable disturbance rejection improves with a more narrowband disturbance spectrum and a smaller loop delay.
To calculate the theoretical optimum performance, simulations have been performed for rejection of the micro-vibration disturbance and a simplified plant model of the opto-mechanical structure only.
Experimental results at TNO show that the predicted maximum rejection ratio is achievable.

3. SPECIFICATIONS AND PERFORMANCE

After completion of component level testing and assembly, the OPD controller was fine tuned to obtain a robust OPD stability in the TNO laboratory. The controller uses a laser interferometer with 0.3 nm resolution for OPD measurement (figure 6).

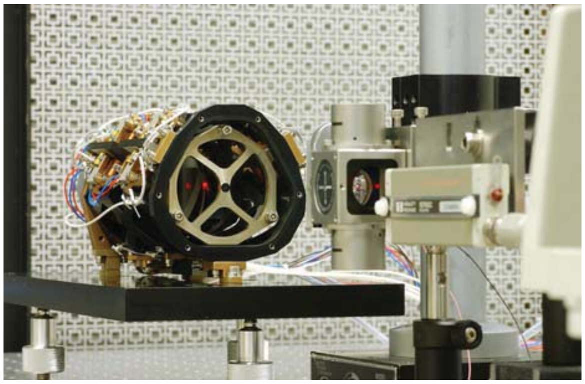

Figure 6 – ODL with laser interferometer

The measured OPD error in the TNO laboratory was better than 0.9 nm RMS, with an open loop disturbance spectrum of 2103 nm RMS [11]. A high-speed laser metrology system was used for OPD control. Based on these measurements, it has been calculated that an OPD error of better than 1 nm can be achieved in the DARWIN spacecraft environment, when the fringe sensor sample rate is higher than 100 Hz.

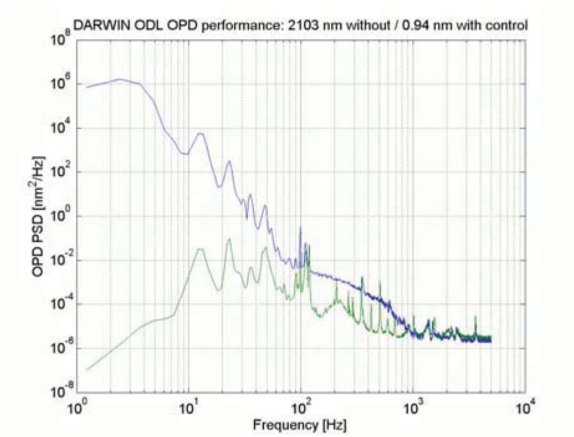

Fig. 7 - Optical Path stability of delay line

In order to verify the structural integrity of the design, the complete ODL was subjected to three deep thermal cycles (between +80 and –185 °C) in a Nitrogen gas environment at a facility of Dutch Space in Leiden, The Netherlands. The magnetic bearing was switched on at the first cold phase and operated successfully. During the entire 2nd and 3rd cycle, the magnetic bearing was kept switched on and operated successfully as well (despite the turbulent gas flow).

After thermal cycling in Nitrogen, the ODL was placed in the 1 meter thermal vacuum chamber at Dutch Space (figure 8) and subjected to one cool down cycle to –185 °C. (moving part –175 °C). Both the magnetic bearing and voice coil operated nominally.

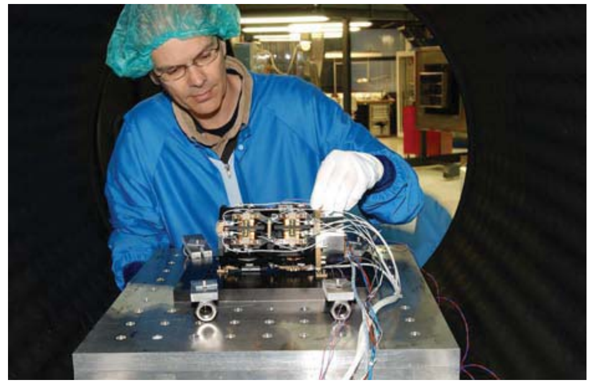

Fig. 8 - Thermal vacuum test at Dutch Space

The verification test program includes Wave Front Error (WFE) measurements at ambient temperature and at 40 K.
The WFE measurement at ambient temperature for the left and right hand apertures is shown in figure 9. The total WFE is 12 nm (vs. required < 31 nm), allowing some margin for cool down to 40K.

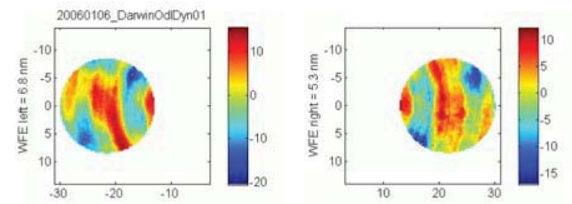

Fig. 9- Wave Front Error of Cat's Eye

The variation of the output beam tilt over the full stroke has been measured to be 0.05 arcsec (0.24 μrad) p-v, limited by the accuracy of the test setup. A cross check measurement of the tilt of the cat's eye revealed that the output beam tilt variation is probably less than 0.1μrad.

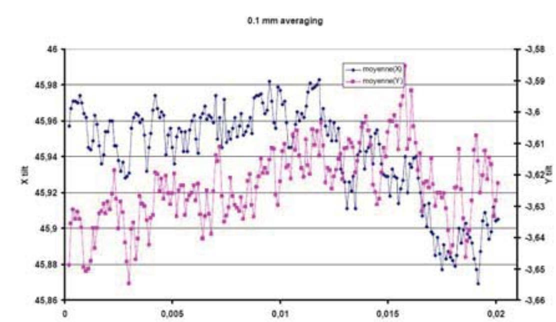

Fig. 10 - Dynamic beam tilt measurements

A summary of other measured parameters measured in the verification test program is given in the table below. Performance parameters at 40K have not yet been measured.

	Requirement	Measured
ODL power consumption - at 40 K in space - at 40 K on ground	< 25 mW	 ~ 2 mW (expected) ~ 20 mW (expected)
Dynamic output beam tilt	< 0.24 µrad	< 0.24 µrad (limited by test setup accuracy)
Output beam lateral deviation	< 100 µm	15 µm
Total RMS wavefront distortion	< 32 nm	12 nm at RT < 32 nm at 40 K (expected)
Mirror surface roughness	-	~ 2 nm RMS
Optical transmission losses - from 0.65 to 4µm - from 4 to 20µm	 < 15% < 6%	 < 15% < 3%
Relative spectral response	< 1e-4	0.90e-4 @ 450 - 850 nm 0.35e-4 @ 2 - 20 µm
Chromatic phase differences - for λ < 1 µm - for λ > 1 µm	 < 0.1 nm RMS < λ/10000 RMS	 < 0.01 nm < λ/13500 RMS @ λ = 4 µm
Relative polarisation rotation	< 0.1°	< 0.0002°
Relative polarisation ellipticity	< 0.1°	< 0.001°
Static beam tip/tilt	< 14.5 µrad	< 4 µrad
OPD - range (optical) - resolution - stability	 > 20 mm < 0.5 nm < 1 nm	 20.4 mm 0.3 nm 0.9 nm (with TNO lab disturbance spectrum)
Dynamic response - ODL rate - Settling time - Damping	 > 250 µm/s < 20 ms > 0.9	 > 20 mm/s < 20 ms > 0.9
Dimensions (including 0-g offloading device)	115 x 115 x 300	114 x 116 x 210 (excluding launch lock)
Mass	< 10 kg (target < 6 kg)	1.7 kg (< 4 kg expected including cable harness and flight electronics)
Design lifetime	10 years	> 10 years

4. FUTURE ACTIVITIES

The current OPD/Magnetic Bearing (MB) controller runs on a real time Linux based PC, in order to have maximum flexibility with respect to control algorithms. The power dissipation of this controller is not representative for the future DARWIN controller. A conventional DSP based control board dissipates in the order of 15 W and would not meet the 2.5 W overall power dissipation requirement.
TNO and SRON are currently developing a low power (< 2 W) FPGA based control board for combined OPD and MB control.
A launch lock is not part of the current development program, but will be required for a future mission. Furthermore TNO recommends doing testing of the optical alignment under zero-g conditions (e.g. parabolic flight).
After the successful completion of the verification program, TNO is looking for a flight opportunity in a future space interferometer or technology demonstrator mission (please contact ben.braam@tno.nl if you wish to discuss this).
TNO is also offering a slightly modified version of this ODL for the ESA GENIE instrument on the ESO VLTI telescopes. This delay technology can also be used in other ground based astronomical instruments.

5. CONCLUSIONS

TNO and its partners have demonstrated that extremely accurate 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 and are wear free. Further verification testing will be done under cryogenic conditions later this year.

6. AKNOWLEDGEMENTS

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