Magnetic Bearing Optical Delay Line

T. van den Dool*[a], F. Kamphues[a], B. Fouss[b], K. Henrioulle[b], H. Hogenhuis[c]
[a]TNO TPD, Stieltjesweg 1, 2628 CK, Delft, THE NETHERLANDS
[b]Micromega-Dynamics, Rue des Chasseurs Ardennais, B-4031, Angleur (Liège), BELGIUM
[c]Dutch Space, Newtonweg 1, 2333 CP, Leiden, THE NETHERLANDS

ABSTRACT

TNO TPD, in close cooperation with Micromega-Dynamics and Dutch Space, has developed an advanced Optical Delay Line (ODL) for use in PRIMA, GENIE and other ground based interferometers.
The delay line design is modular and flexible, which makes scaling for other applications a relatively easy task.
The developed technology can also be applied in future cryogenic space interferometers, such as DARWIN, and TPF-I.
The ODL has a single linear motor actuator for Optical Path Difference (OPD) control, driving a two-mirror cat's eye with SiC mirrors and CFRP structure. Magnetic bearings provide frictionless and wear free operation with zero-hysteresis. The delay line has been assembled and is currently being subjected to a comprehensive test program.

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

1. INTRODUCTION

TNO TPD and its partners have a broad experience with developing delay lines. Recent projects include the delay lines for the ASTRIUM Nulling Breadboard (under ESA contract), the ESO VLTI delay lines (developed by Dutch Space and TNO TPD) and a DARWIN cryogenic breadboard delay line (under ESA contract) [13].
Based on this experience, a delay line has been developed with magnetic bearings for use in ground based instruments, such as GENIE and PRIMA. The generic long stroke actuator and guiding technology could also be applied for missions such as TPF-I.

Fig. 1. ESO VLTI Delay Line (photo Dutch Space)

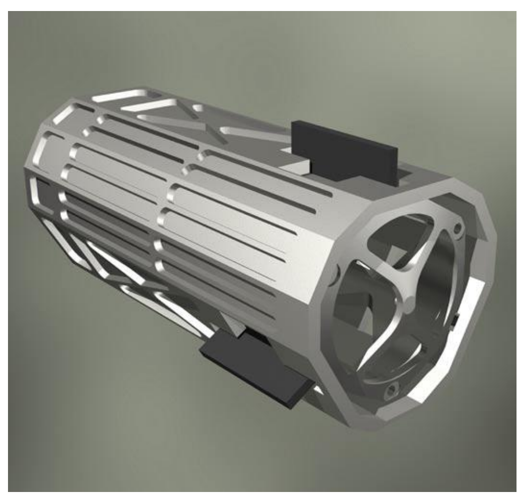

Fig. 2. ESA DARWIN breadboard cryogenic Delay Line

* dendool@tpd.tno.nl; phone 31-15-26 92 457; fax 31-15-26 92 111; www.tpd.tno.nl

Space Systems Engineering and Optical Alignment Mechanisms, edited
by Lee D. Peterson, Robert C. Guyer, Proceedings of SPIE Vol. 5528
(SPIE, Bellingham, WA, 2004) · 0277-786X/04/$15 · doi: 10.1117/12.549431

The main requirements for the Advanced Optical Delay Line Demonstrator have been derived from the ESO specifications for the PRIMA differential delay lines (DDL) [1], with an additional anticipated requirement for OPD stability for GENIE. An overview of the main characteristics is given in table 1.

Operational temperature	Ambient
Pressure	Ambient and light vacuum (ca. 1 mbar)
Temperature	Ambient
Mechanical environment	The DDL shall meet their performance characteristic requirements under micro-seismic activity as specified in VLT-SPE-ESO-10000-0004. They shall also sustain earthquakes with little or no damage. A park mode is foreseen when a DDL does not need to be active during observation. The retro-reflector shall be put at a fixed, well-known and pre-defined position outside of its active range.
ODL stability (with single actuator*)	< 1.0 nm RMS (over an entire observation)
OPD range (mechanical)	70 mm
Slewing time Slewing velocity	<5 seconds >7 mm/s
Fringe tracking and observation mode velocity	-500 to +500 µm/s
Dimensions (W x L x H)	220 x 900 x 300 mm
Overall power dissipation	< 1 kW (for 8 delay lines)
ODL power dissipation in interferometer lab	< 5 W (per delay line)
F.o.V.	15 arcmin
Pupil transfer	Yes
Distance between input and output beam	120 mm
Optical beam diameter	>18 mm In combination with the pupil transfer and F.o.V. requirements, this leads to a free aperture of 55 mm
Output beam lateral displacement Output beam tilt (both over the full actuation range)	< 25 µm <1.5 arcsec
Wavelength range	0.42 – 28 µm
Wavefront distortion	<25.0 nm RMS
Transmission	From 0.42 to 1.0 µm >80% From 1.0 to 28 µm >98%

* A second actuation stage is optional

Table 1. Advanced Optical Delay Line demonstrator main characteristics

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

- TNO TPD – Project management, systems engineering, optical design and OPD control engineering
- Micromega-Dynamics – Guiding system development
- Dutch Space – Linear motor amplifier and controller electronics development

2. CONCEPT SELECTION

The selection of the conceptual design for the advanced Optical Delay Line, for use in GENIE and PRIMA, is described in detail in [14].

The selected concept for the advanced ODL consists of:

Optics: 2-mirror cat's eye

Guiding: Magnetic bearings constraining 5 DOF with eddy current sensors and central digital controller

Actuation: Single stage with linear motor actuator and digital OPD controller.

The delay and its individual components are shown in figure 3.

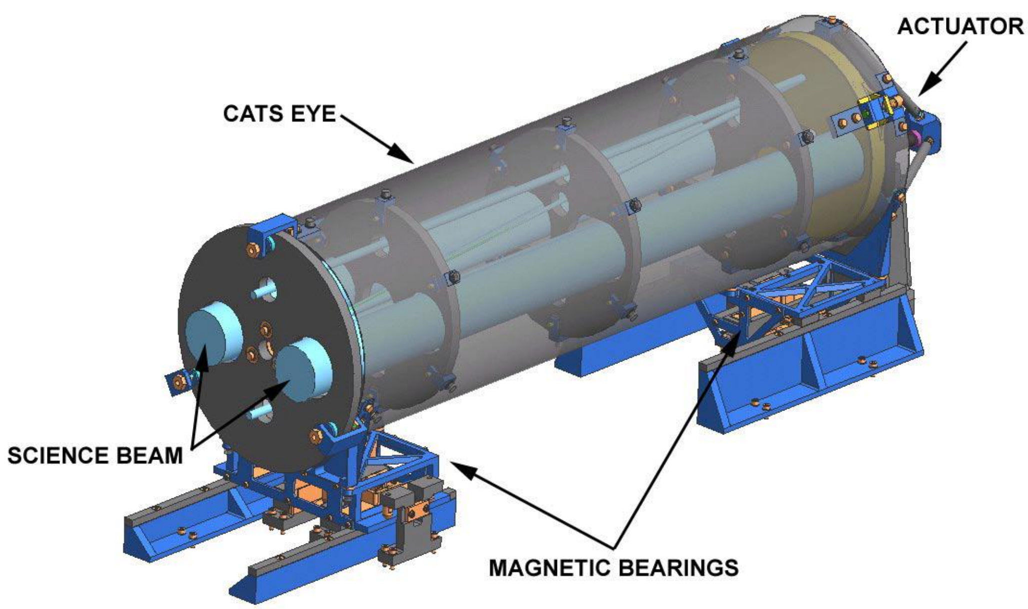

Fig. 3. Magnetic Bearing Optical Delay Line for PRIMA and GENIE

3. DESIGN OF THE OPTICAL DELAY LINE

3.1. Retro-reflector

The retro-reflector consists of a two-mirror cat's eye, containing one parabolic and one flat mirror. The parabolic M1 has a diameter of 200 mm (ESO I/F requirement) with a focal length of 700 mm. The flat M2 has a diameter of 25 mm.
The cat's eye has two openings for the science beam and two for a laser metrology beam.
The optical configuration is shown in figure 4.

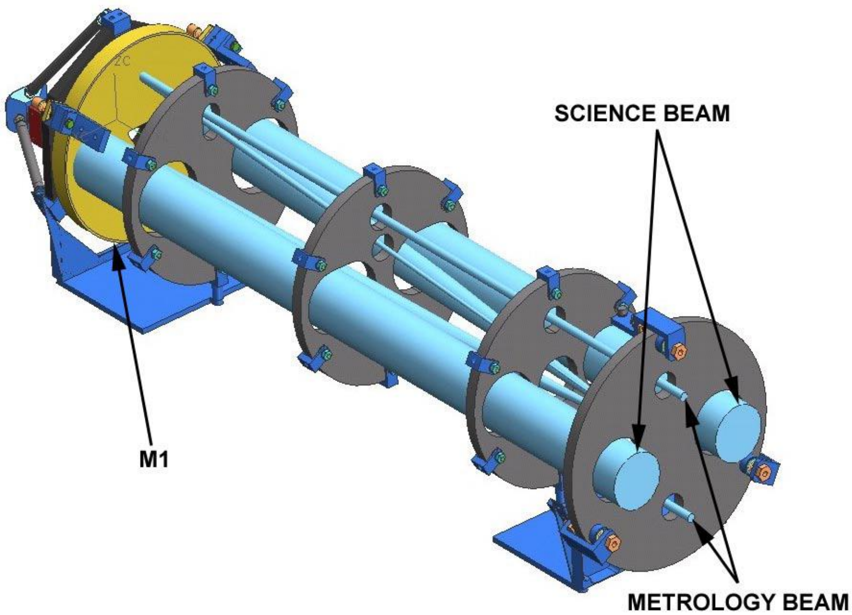

Fig. 4. Cat's Eye optical configuration

Structure

The use of magnetic bearings requires a high structural stiffness of the cat's eye, to avoid control flexibility interactions and subsequent bearing instability.
This calls for a lightweight retro-reflector design, using advanced materials such as CFRP and SiC.
The cat's eye consists of a tubular structure with internal baffles to suppress local modes.

The first natural frequency of the cat's eye (including mirrors) is 1082 Hz.

The tube is made from high modulus CFRP prepreg material and has a quasi isotropic layup.
In order to avoid excessive moisture expansion, a cyanate resin is used instead of epoxy resin.
The selected prepreg material is M55J/CE3, made by ATK-COI.

The internal baffles are made of sandwich panels with T300 face sheet and foam core. The baffles are shown in figure 5.
The open sides of the sandwich panels are covered with a single layer of CFRP, to avoid contamination of the mirrors by trapped dust particles.
The entire CFRP structure, including the precision machining, is manufactured by Futura Composites in the Netherlands.

Fig. 5. CFRP baffles

Mirrors

The CTE of a quasi isotropic M55J laminate is around 1E-6 m/m/K and requires mirrors with matching CTE for maximum (thermal) stability. Various suitable materials are available (Zerodur, ULE, SiC), but SiC offers the best performance in terms of specific stiffness.
The SuperSiC material, made by POCO Graphite in the USA, was selected for its high purity and relative ease of manufacturing. The mirror blanks are machined out of pure graphite and then converted to SiC. The Young's modulus is slightly lower than sintered SiC, but this can be offset by producing thinner wall thicknesses during machining.
The resulting lightweighted mirror has an areal density of approximately 15 kg/m^2.
The first natural frequency is around 2 kHz.

After SiC conversion, the mirrors are CVD coated and polished.
Polishing of both parabolic and flat mirror will be done in house by TNO TPD in cooperation with an external partner.

After polishing, a reflective Gold coating will applied to both mirrors to obtain the required transmission.

The parabolic M1 mirror is shown in figure 6.
The flat M2 mirror is shown in figure 7.
The M1 is mounted in flexures to compensate for the small mismatch in CTE (around 1.3E-6 m/m/K) between the CFRP structure and the mirrors. For similar reasons, a set of metal adjustment washers are added between M2 and the structure to compensate for variations in focal length.

The delay line is currently being tested with dummy mirrors. The polishing of the SiC mirrors will be completed before the end of 2004.

Fig. 6. ODL SiC M1 mirror (200 mm diameter)

Fig. 7. ODL SiC M2 mirror (50 mm diameter)

3.2. Guiding Mechanism

TNO TPD applies a minimum-number-of-stages philosophy to all delay lines it develops.
A smaller number of actuation stages simplifies the OPD control algorithm, reduces mechanical complexity and improves the optical quality of the outgoing beam.

The guiding mechanism is based on active magnetic bearings. The magnetic bearing system has been designed by Micromega-Dynamics in Belgium, who have extensive experience with magnetic bearings, including application in space mechanisms such as MABE [12] and the DARWIN breadboard cryogenic delay line [13].
Magnetic bearings offer ultra smooth guiding and have a number of advantages over other guiding options, such as flexures, ball bearings and air bearings.
Another benefit of active magnetic bearings is the option of guiding error correction, reducing the requirements on mechanical tolerances, which could be more cost effective.

Magnetic bearings are relatively simple, and being contactless, do not require lubrication and do not wear. The inherent cleanliness makes them highly suitable for sensitive optical instruments.

In order to limit the power dissipation in the ODL, permanent magnet based reluctance force actuators will be used for the bearings. As the delay line requires operation in a 1g environment, the permanent magnets carry 100% of the mass of the moving part, to minimise power dissipation. The active coils are only used for balancing and dissipate only a few milliwatts.

Figure 8 shows the magnetic bearing configuration. A (moving) piece of soft iron is attracted by a permanent magnet. The system is inherently unstable. The permanent magnet is located in the middle of two soft iron parts. The permanent magnet produces a constant magnetic flux and the coils generate a variable magnetic flux that is added (or subtracted) to (from) the constant one. Eddy current sensors provide position information to the bearing controller, which in turn, keeps the moving soft iron part in its centre position.

The advanced ODL has five magnetic bearings to constrain five degrees of freedom (the OPD controller constrains the other degree of freedom). The centralised magnetic bearing controller will run on the same PC as the OPD controller.

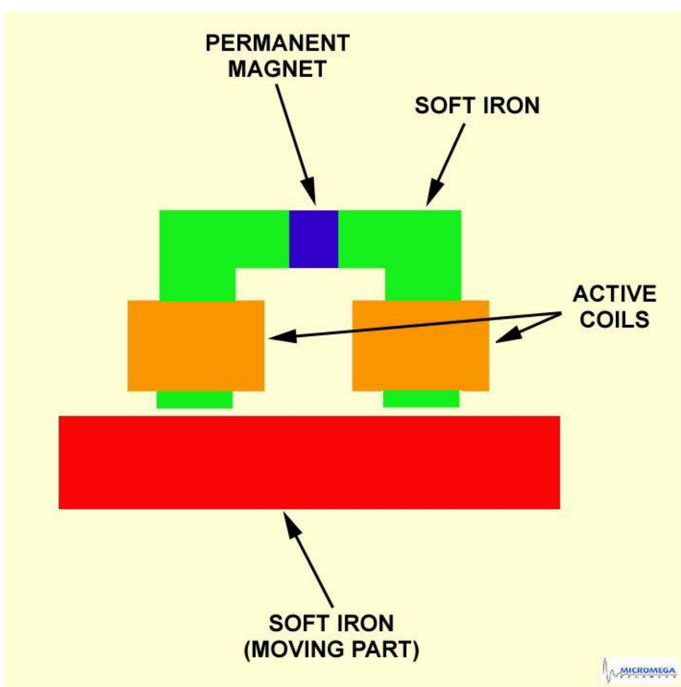

Fig. 8. Active magnetic bearing

3.3. Actuation and OPD Control

Actuator

The cat's eye is actuated by a miniature linear motor. The development of the motor controller electronics is done in close cooperation with Dutch Space, and is based on the experience gained by Dutch Space with the VLTI delay lines.

The linear motor voice coil actuator is located at the back of the cat's eye and acts in the C.o.G. of the delay line.
The coil assembly is attached to the static part of the ODL and the magnet rod is attached to the moving part, thus preventing disturbance forces caused by electrical wires. The magnet rod is attached to the cat's eye structure with a CFRP truss, as shown in figure 9.

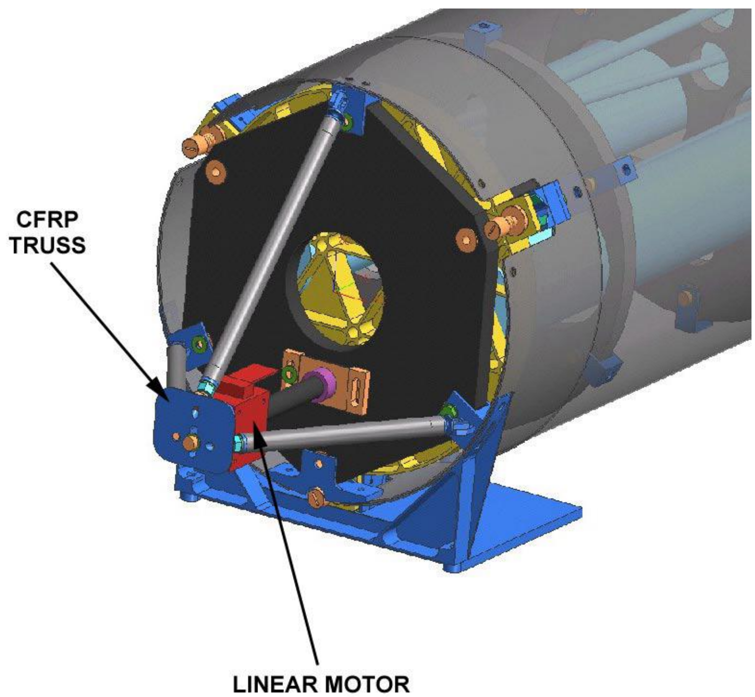

Fig. 9. Miniature Linear Motor

OPD controller

The advanced ODL will use a digital controller. The controller will be implemented on a real-time Linux PC to enable quick adjustment and fine tuning of control parameters during the development phase.

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.
Control simulations have been performed to predict the controller performance with various loop delays and OPD sensor sampling rates.

Experimental results at TNO TPD and Dutch Space on other delay lines, show that the predicted rejection ratio is achievable [3, 8, 10]. For the GENIE and PRIMA delay lines an attenuation of the disturbance of >70 dB appears to be feasible, enabling better than 1 nm RMS OPD stability.

OPD control performance testing will commence in September.

4. CONCLUSION

Analyses show that the design of an advanced single stage ODL can meet the requirements for GENIE and PRIMA.

The advanced ODL demonstrator has been assembled and a comprehensive test program has started in July 2004. The assembled ODL is shown in figure 10.

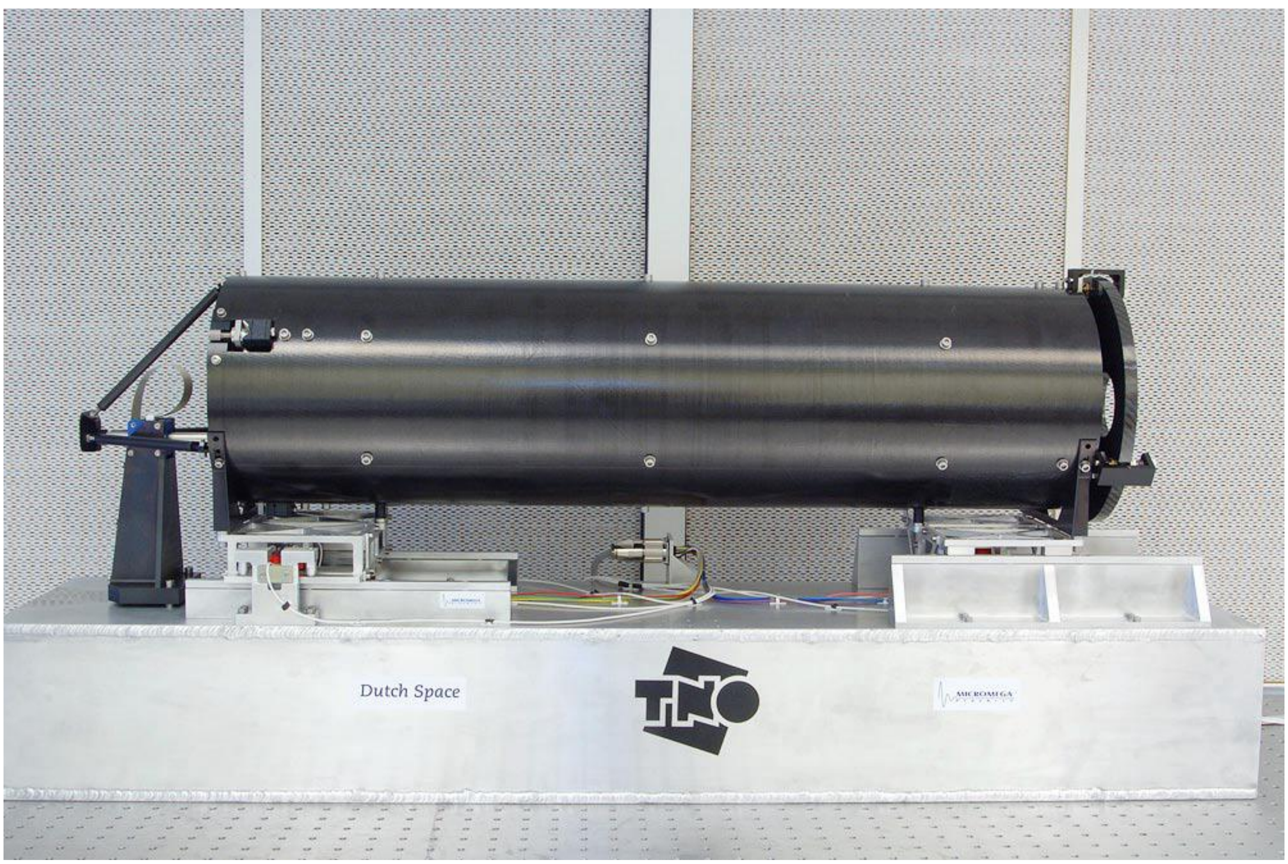

Fig. 10. GENIE/PRIMA ODL demonstrator

AKNOWLEDGEMENTS

TNO TPD would like to thank Joost Carpay (NIVR), Vincent Vlasblom (Futura Composites), Ed Lettner (ATK-COI) and Elmer Pennewaard (POCO Graphite) for their support during the development of the advanced delay line.

REFERENCES

[1] Prima Differential Delay Line (DDL) Performance & Technical Requirement Specifications, ESO VLT-SPE-ESO-15720-2209 (http://www.mpia-hd.mpg.de/PRIMA-DDL/)

[2] B. Snijders et al., "Free-beam delay line for a multi-aperture optical space interferometer stabilized on a guide star", SPIE Vol. 2209, 1994

[3] B.C.Braam et al., "Kinematic six-ball guide for long stroke optical delay line", Proc. Sixth European Space Mechanisms & Tribology Symposium, Zurich (Switzerland), 1995, ESA SP-374, August 1995

[4] R.J. Calvet et al., ‘Enabling design concepts for a flight-qualifiable optical delay line’, SPIE Vol. 3350 (1998), pp. 35-47.

[5] S. Mekid and M. Bonis, Conceptual design and study of high precision translational stages: application to an optical delay line, Precision Engineering (1997), Vol. 21, No. 1, p. 29 – 42.

[6] 'Optical Delay Line Nanometre Level Pathlength Control Law Design For Space-Based Interferometry', Robert L. Grogan, Gary H. Blackwood, and Robert J. Calvet. SPIE, Kona, Hawaii, March 1998, pp.14-25

[7] Y. Honma et al., ‘Development of the fine delay line in the Mitaka optical and infrared array (MIRA) project’, SPIE Vol. 3350 (1998), pp. 192 - 201.

[8] 'Active Vibration Control for an Optical Delay Line', N.J. Doelman, T.C. van den Dool. Proc. of Active 2002, pp.887-898

[9] B. Koehler et al., ‘Optical delay line for stellar interferometer’, SPIE Vol. 1236 (1990), pp. 463 - 472.

[10] F. Derie et al., ‘VLTI delay lines: design, development, performance results, and commissioning on site’, SPIE Vol. 4006 (2000).

[11] A. Molenaar, H.F. van Beek, and M.J.L. Sanders, " A New Linear Magnetic Bearing Configuration for High Accuracy Positioning", in Proceedings of MAG97: Magnetic Bearings, Magnetic Drives and Dry Gas Seals Conference & Exhibition (P. Allaire, ed.), (Alexandria, Virginia), pp. 313–322, Technomic Publishing Company, Inc, July 1997

[12] MABE, Fine Precision Mechanism Based on Magnetic Bearing Technology, Micromega Dynamics – Executive Summary (ESA Contract No 13676/99/NL/PA)

[13] T. van den Dool et al., ‘The design of a breadboard Cryogenic Optical Delay Line for DARWIN’, SPIE Vol. 5495-40 (2004)

[14] T. van den Dool et al., ‘Advanced Optical Delay Line Demonstrator’, SPIE Vol. 5495-41 (2004)