THE DEVELOPMENT OF A BREADBOARD CRYOGENIC OPTICAL DELAY LINE FOR DARWIN

T.C. van den Dool [(1)], W.L.M. Gielesen [(1)], F. Kamphues[(1)], B.C. Braam[(1)], N. Loix [(2)], P.P. Kooijman[(3)], G. Velsink[(4)], Y. Stockman [(5)], J. Benoit [(6)], F. Sève [(7)]

[(1)] TNO Science & Industry, Stieltjesweg 1, 2628 CK, Delft, The Netherlands, Email: ben.braam@tno.nl
[(2)] Micromega-Dynamics,Rue des Chasseurs Ardennais,B-4031, Angleur (Liège), Belgium, Email: nloix@micromega-dynamics.com
[(3)] SRON, Sorbonnelaan 2, 3584 CA, Utrecht, The Netherlands, Email: p.p.kooijman@sron.nl
[(4)] Dutch Space, Newtonweg 1, 2333 CP, Leiden, The Netherlands, Email: g.velsink@dutchspace.nl
[(5)] CSL, Parc Scientifique du Sart Tilman, Angleur (Liège), Belgium, Email: ystockman@ulg.ac.be
[(6)] Thales Alenia Space, Bld. du Midi, F-06156 Cannes La Bocca, France, Email: jeremie.benoit@thalesaleniaspace.com
[(7)] SAGEIS-CSO, 70, Avenue des Martyrs, 38000 Grenoble, France, Email: f.seve@sageis-cso.fr

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. The breadboard delay line is representative of a flight mechanism. The optical design is a two-mirror cat's-eye. A single stage 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 Optical Path Difference (OPD) control. The verification program, including functional testing at 40 K, has been completed and showed compliance with all important requirements.

1. INTRODUCTION

ESA is developing the Darwin mission with a planned launch date around 2020 [1]. Its principal objectives are to detect Earth-like planets around nearby stars. It will consist of 3 or 4 optical telescopes observing infrared light. The telescopes will cooperate as a nulling interferometer to destructively extinguish the light from the star and simultaneously amplify the planet's light. The presence of life might be observed by analyzing the wavelength content of the light reflected by the planet.

Optical delay lines in a central hub satellite serve to equalize the optical path lengths down to sub-nanometer level without introducing optical deviations such as wavefront aberrations, beam tilts, lateral beam shifts, and polarization errors. If the light beams fall on a detector/camera, an interference pattern will show up that enables observation of the star and its accompanying planet with a resolution far better than a single telescope would allow.

The design, implementation, and testing of these optical delay lines by TNO (see Figure 1) is described in this paper. Within this study, the responsibilities were 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.
- Centre Spatiale de Liege (CSL): coating engineering and 40K Thermal-Vacuum (TV) facility.
- Dutch Space: thermal modeling and development tests at 100K.
- Alcatel Alenia Space: mission level consultancy and verification test program (in co-operation with Sageis-CSO).

The project started in 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 testing at 40 K, was carried out in 2006. The final presentation at ESTEC was on 12 December 2006.

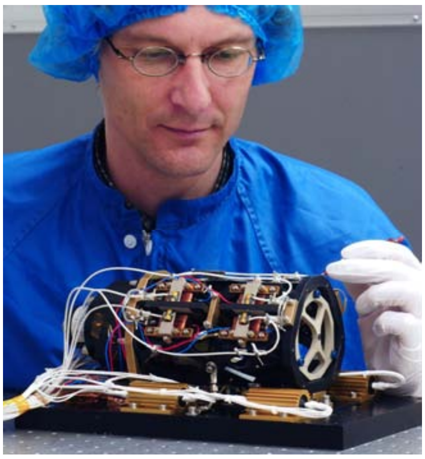

Figure 1. The assembled TNO dynamic ODL.

Proc. '12th Euro. Space Mechanisms & Tribology Symp. (ESMATS)', Liverpool, UK, 19–21 September 2007 (ESA SP-653, August 2007)

2. REQUIREMENTS

The main requirements are as follows [3]:

- Optical beam diameter: > 25 mm
- OPD stroke: 20 mm (10 mm mechanical)
- Dimensions: < 300 x 100 x 100 mm
- Mass: <10 kg (target: <6 kg)
- Space vibrations: 100nm rms (-40dB/dec for f>1 Hz)
- OPD stability: < 1 nm RMS (0.5 nm mechanical)
- Dynamic response: 25 µm step in <20 ms.
- Overall power dissipation: < 2.5 W
- Power dissipation in ODL: < 25 mW
- Output beam tilt: < 0.24 µrad
- Output beam lateral shift: < 100 µm
- Wavelength range: 0.45 - 20 µm
- 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 µm 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

Accommodating the required beam diameter of 25 mm and OPD stroke of 20 mm is hard within the given envelope of 300x100x100 mm and with the power dissipation not exceeding 25 mW.

3. DESIGN DESCRIPTION

The basic structure of the ODL is arranged around a cat's-eye with a focal distance 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. A cat's-eye can also accommodate an optional pupil imaging.

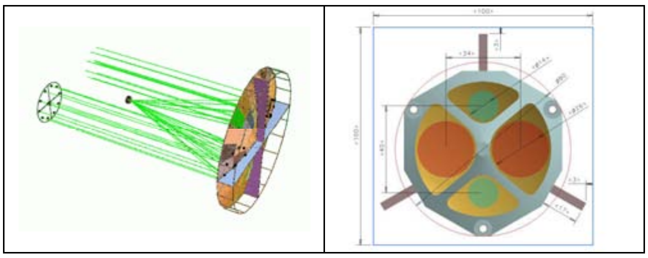

Figure 2. Left: the optical design of the ODL is a cat's-eye with a primary 63 mm parabolic mirror (M1) and a small 6 mm secondary mirror (M2). Right: front view of the ODL with 25 mm science beam entrance and exit and 14 mm metrology beam (optional).

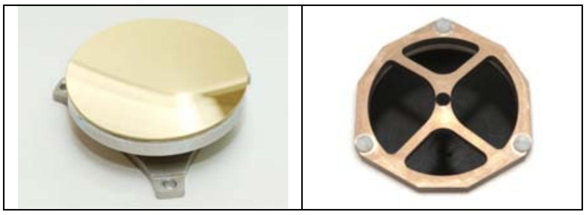

Figure 3. Photograph of the ODL mirrors M1 (63 mm parabola at left) and M2 (6 mm flat at right). Both are 6061-T6 Aluminum, Alumiplated, diamond turned, and gold coated. The M1 mirror support is a so called "wine-glass" type.

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 alumiplated to reduce surface roughness after diamond turning (see Figure 3). Both mirrors are gold coated to obtain the required reflectivity.

A single stage OPD actuation scheme has been adopted. It leads to low complexity. The power dissipation of a single stage is still very low, and it does not hamper the optical performance (no focus change of the cat's-eye due to a piezo actuated secondary mirror). The self-induced vibrations are a little higher than with a double stage actuation system, but still considered acceptable.

Magnetic Bearings (MBs) based on reluctance type electromagnets are used for the guiding system (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, 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 6^{th} MB coil set for extra redundancy.

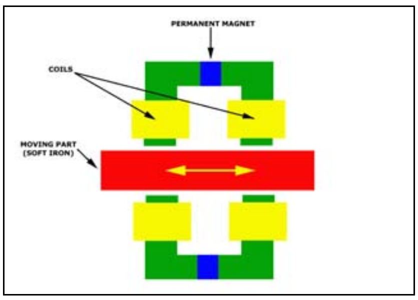

Figure 4. Magnetic bearing design; a soft iron moving target (red) is retained in a non-stable equilibrium by 2 yokes (green) with attracting permanent magnets (blue). Coils (yellow) and an appropriate controller with eddy current sensors actively preserve the middle position. Five of these are used in the ODL.

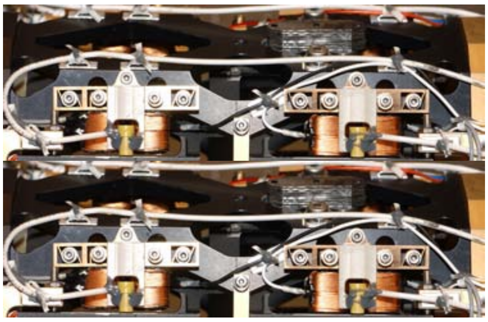

Figure 5. Close-up photograph of 2 integrated magnetic bearing assemblies.

For OPD actuation a fully redundant 2-coil Lorentz force motor is implemented (see Figure 6). 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 7). An ultra low noise current amplifier with a large dynamic range powers the voice coil.

Figure 6. Photograph of the OPD actuator; a Lorentz motor. Left: magnet assembly on flexures which is mounted on the back of the M1 parabolic mirror. Right: the voice-coil which is mounted on a cap on the ODL stator.

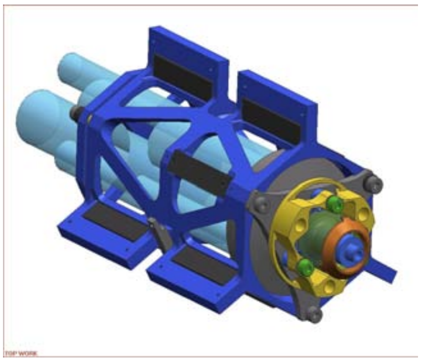

Figure 7. Rotor (moving part) design with parabolic mirror at the back. The magnet of the voice-coil actuator is mounted on top of it through a flexure interface. It has 6 flaps (4 visible) with soft iron magnetic bearing targets (black). The science and metrology beams are shown in transparent light blue.

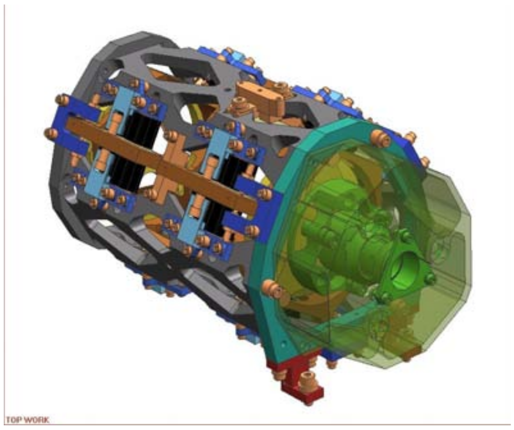

Figure 8. Complete ODL design with the rotor (moving part) inside the stator. The voice-coil is mounted on a separate cap on the back-side.

The flight model of the ODL will need a launch lock. A (re)locking actuator has not been implemented in the breadboard. Only a simple manual transport lock 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. Also the voice coil magnet assembly and its flexible support on the M1 mirror are capable of carrying the locking and launch loads. A pin in the centre of the voice-coil magnet can carry the load of a future locking actuator.

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.

Apart from the dynamic ODL, which has the magnetic bearings and OPD control, a static ODL is realized to enable differential testing in Darwin-like breadboards (see Figure 10). The static delay line has exactly the same optical layout but the support is a simple tube on three legs (see Figure 9).

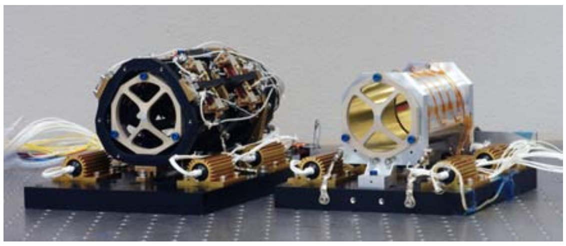

Figure 9. Left: dynamic ODL. Right: static ODL.

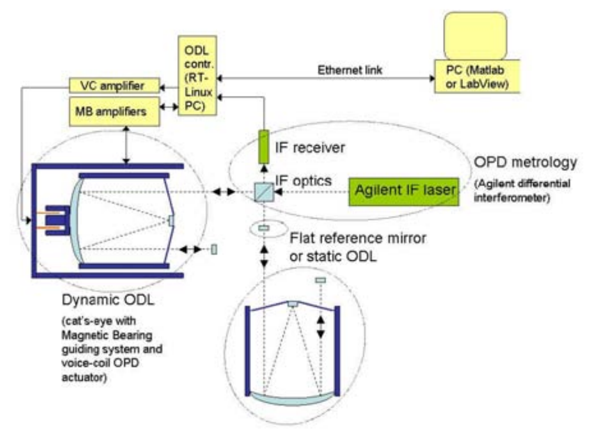

Figure 10. Example of an ODL breadboard test set-up.

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.

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.

4. VERIFICATION PROGRAM

During development and integration a comprehensive tests program was carried out by TNO and SRON in 2005 preceding the verification program. 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 was extensively tested at ambient temperatures.

Verification of the optical coating requirements of the mirrors was mainly done at sample level at ambient temperatures by CSL. The coating tests included the following measurements:
- Mirror surface roughness
- Coating adhesion before and after thermal cycling
- Optical transmission
- Relative spectral response
- Chromatic phase differences
- Relative polarization rotation
- Relative polarization ellipticity

Alcatel Alenia Space, in co-operation with Sageis-CSO, carried out the final verification test program of the assembled ODL. It comprised an ambient test program and cryogenic test programs at 120 K and 40 K. The ambient test program was carried out in a laboratory at Sageis-CSO in Grenoble. 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).

Sageis-CSO developed a specific optical bench to test and qualify the ODL (see Figure 11). The test bench is divided in two parts:
- A fixed part that contains the laser and the Agilent interferometer (IF), which is not only used for verification, but also to drive the ODL. The Agilent interferometer has a resolution of 0.3 nm in double-double pass configuration (2 beams, both reflected back at the exit of the ODL).
- A mobile part that contains various optical instruments. It allows for 3 main configurations :
  - o A Shack-Hartmann sensor for Wave Front Error (WFE) measurements.
  - o An electronic autocollimator for relative tilt variation measurements over the actuation range.
  - o A special optical head for lateral deviation, optical transmission, and polarization measurements.

During measurements, the ODL is driven by a test bench PC and specific software (LabView). This application is driving the test equipment and the ODL through the ODL control PC (see Figure 12). The ODL tests are performed largely automatically with scripts that command the ODL displacement and the controllers of the test equipment.

Figure 11. 120 K thermal-vacuum (TV) verification test setup at the Dutch Space TV facility with the HP IF (left) and the HASO WFE equipment (right).

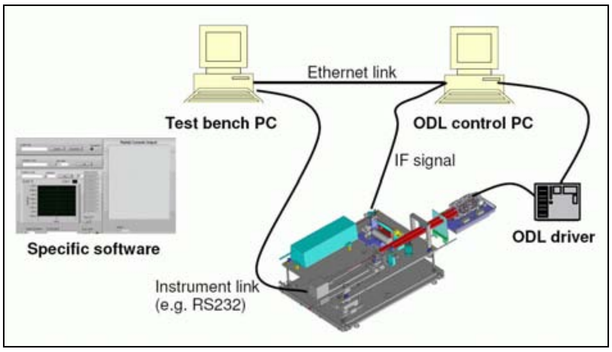

Figure 12. Verification test setup.

In WFE measurement configuration, the test bench is equipped with a HASO Shack-Hartmann WFE analyzer in double pass configuration (see Figure 13 and Figure 14). The HASO system is combined with a collimator, allowing the acquisition of the WFE map over a 25 mm pupil in real time, with a high sampling rate (acquisition time of 200 µsec). The WFE is checked for various positions on the ODL stroke. The measurement accuracy is 8 nm RMS over an aperture of 25 mm. The measurements are repeated for 3 field of view angles (0 and ±3 arcmin).

Tilt measurements were carried out with a Möller-Wedel Elcomat HR electronic autocollimator, used in double pass configuration (see Figure 15). A precision of 0.02 arcsec is reached on the measurement of the relative tilt variation over the full actuation stroke of the ODL, which is close to the detection limit of the autocollimator.

Tilt measurements were done while the ODL was scanning 10 times over the whole stroke back and forth at 1 mm/s. By synchronizing acquisition and time filtering, external vibrations could be largely removed from the acquisition signal. The ODL tilt variation is then calculated over the full stroke by 2 mm OPD stroke averaging. This was all needed to reach the 0.02 arcsec measurement accuracy. The measurements are repeated for 5 field of view angles (0, ±1, and ±3 arcmin).

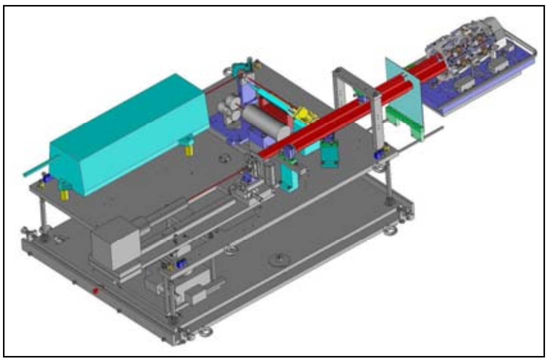
Figure 13. WFE verification setup with a HASO Schack-Hartmann analyzer.


Figure 14. HASO Shack-Hartman WFE analyzer with 25 mm collimator and reference mirror.

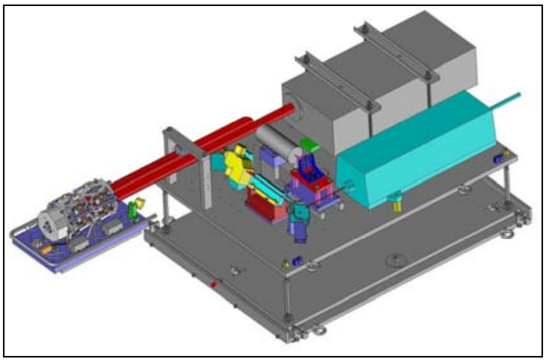
Figure 15. Beam tilt verification setup with a Möller-Wedel autocollimator.

A special optical head has been developed for various measurements. The detection unit can be exchanged for these measurements:

- Optical decentre (lateral beam shift/deviation) using a PSD (Position Sensitive Detector).
- Optical transmission using a photo detector.
- Polarization using a polarimeter which gives the stokes parameters (S0, S1, S2 and S3) of the optical beam.

To increase measurement accuracy for the lateral deviation a scanning measurement has been used at 1 mm/s. 10 full stroke back and forth translations are averaged and the resulting samples are averaged in 2 mm OPD intervals. The measurements are repeated for 5 field of view angles (0, ±1, and ±3 arcmin).

The transmission efficiency was only measured at a wavelength of 633 nm and served to verify the tests at component level at ambient temperatures.

All measurements were carried out with at a wavelength of approximately 633 nm.

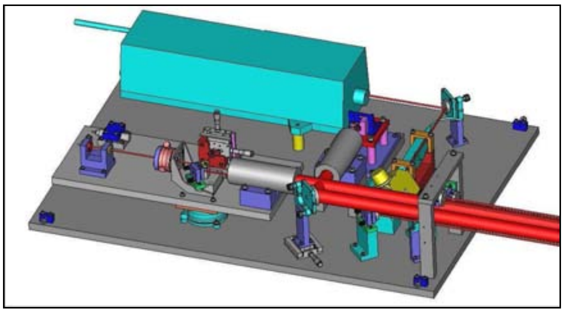
Figure 16. Verification test setup for lateral beam shift, transmission efficiency, and polarization.

Figure 17. Verification test setup in CSL’s Focal-2 thermal-vacuum facility in Liege, Belgium.

The test setup was evaluated during a 120 K nitrogen cooled thermal-vacuum (TV) campaign at the TV facility of Dutch Space in Leiden, the Netherlands (see Figure 11).

The final 40 K thermal vacuum verification program was carried out in the liquid Helium cooled Focal-2 facility of CSL in Liege, Belgium (see Figure 17). The test bench was integrated outside the Thermal Vacuum (TV) facility to give access for adjustment and configuration changes of the test bench. Optical performance measurements are done through a high quality optical window. The WFE contribution of the window was measured and subtracted from the ODL WFE.

Both optical delay lines (dynamic and static) are located inside the TV facility (see Figure 18). The Static ODL is only subjected to the cryogenic environment. No measurements are made on the Static ODL during the TV test, but the WFE is measured before and after the test.

The ODL is fully enclosed in a radiative tent (6 assembled square panels), fed with liquid Helium at 20 K. An additional He-pipe around the ODL gives conductive cooling via thermal straps to the Aluminum baseplates supporting the two ODLs. The baseplates are isolated from the “warm” ground at 300 K through isolating stages (Permaglass washers and a Quartz tube).

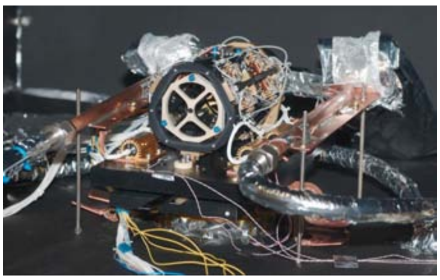

Figure 18. Dynamic ODL in CSL’s Focal-2 TV facility with He-piping.

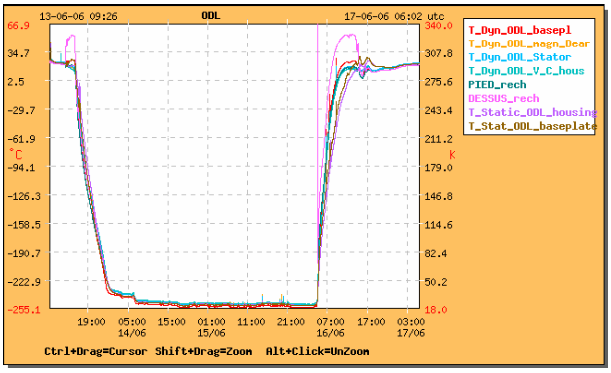

Figure 19. Temperature history during the 40 K verification campaign in CSL’s Focal-2 facility.

Thermal heaters are integrated on the baseplates to control the thermal cooling and heating speeds, ensuring thermal uniformity (gradient minimization), prevent contamination of the optics, and allow quick heating-up at the end of the test. The thermal design ensured that the whole test campaign could be run at the Darwin operational temperature of 40 K or lower (25 K was reached during the test campaign, see Figure 19).

5. PERFORMANCE

The OPD stability during the 40 K TV test at CSL was between 5 and 10 nm rms (see Figure 20). This was considerable higher than the stability reached during the integration phase in the TNO laboratories: 0.9 nm rms. The reason for this is that the vibrations in this TV facility are considerably (~10x) higher than in the TNO laboratory at high frequencies (between 50 Hz and 500 Hz). The performance could have been improved by retuning the OPD controller but there was no time for this during the TV cycle.

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. 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 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 operated at the equilibrium point of the permanent magnets.

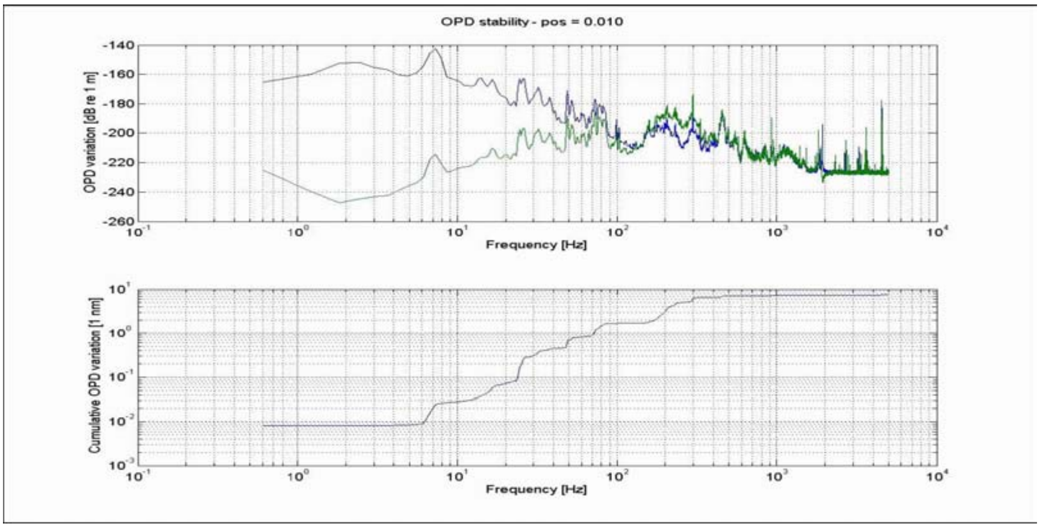

Figure 20. Open and closed loop OPD stability PSD (upper plot) and cumulative PSD (lower plot) during the 40 K TV test (-180 dB = 1 nm^2/Hz, -200 dB = 0.01 nm^2/Hz, etc.).

The lateral beam shift of the output beam during a full 20 mm OPD scan is less than 10 µm peak-peak , which is only 10% of the required 100 µm (see Figure 21).

The repeatability of the measurement procedure with the autocollimator was in the order of 0.05 arcsec, similar to the requirement for the ODL. The measurements gave results in this order of magnitude (Figure 22), which shows that the ODL performance is at least this good.

To further verify the beam tilt stability, the tilt of the rotor was measured (see Figure 23). It proved to be in the order of 40 µrad, far better than the 400 µrad 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 verified that the rotor tilt could be further reduced to 0.5 µrad with a lookup table for the magnetic bearing steering.

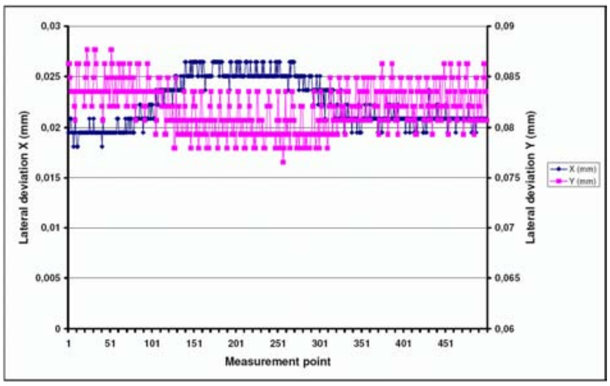

Figure 21. Dynamic beam shift measurement result in horizontal (X) and vertical (Y) directions.

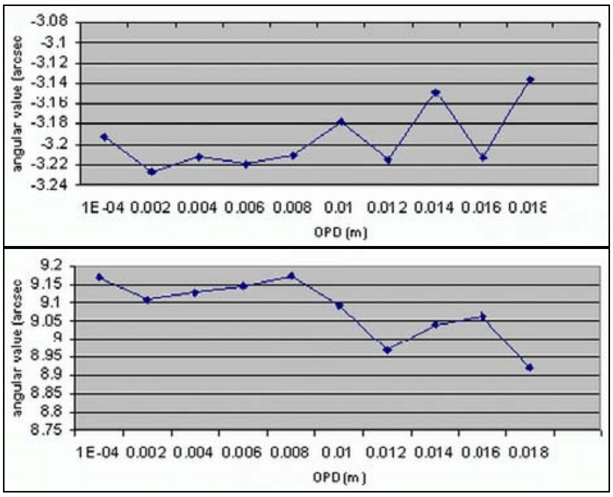

Figure 22. Dynamic beam tilt measurement in horizontal (X, upper plot) and vertical (Y, lower plot) directions during a full 20 mm OPD scan.

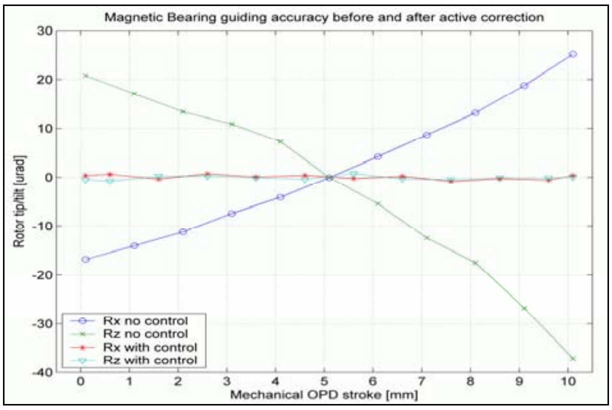

Figure 23. Dynamic rotor tilt before and after active compensation with the magnetic bearings.

The verification test program included Wave Front Error (WFE) measurements at ambient temperature and at 120 K and 40 K and for 3 field of view angles (0 and ±3 arcmin). The final WFE at ambient was better than circa 20 nm = lambda/30 rms for a beam diameter of 17 mm and all field of view angles (see Figure 24).

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

All other requirements are also met. Especially the total mass is relative low: 1.7 kg compared to the required 10 kg (or 6 kg target). The expected future mass including cabling and flight electronics is around 4 kg.

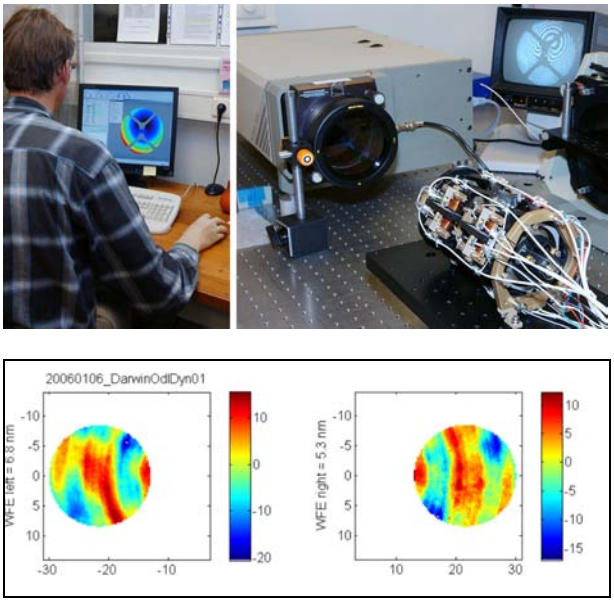

Figure 24. WFE measurements at ambient during integration of the ODL.

6. 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.

7. ACKNOWLEDGEMENT

The work has been performed under ESA contract 17.747/03, with support from the Netherlands's Agency for Aerospace Programs (NIVR), in preparation for the DARWIN mission. TNO would like to thank Josep Maria Perdigues Armengol (ESA-ESTEC), Joost Carpay (NIVR), and Gustavo Vallejo (Alumiplate) for their support during the development of the delay line.

8. 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