

Title: **Multi-Aperture Imaging Interferometer**
ABSTRACT

Customer: ESA

Contract No.: ESTEC/Contract No. 14827/00/NL/CK including
CCN01, CCN02, and CCN03

ESA Technical Manager: Dr. Z. Sodnik

Contractor: Astrium GmbH (Germany)

Project Manager: Dr. R. Flatscher / Astrium, Dep. ED411

Subcontractors: TNO-TPD
TU-Wien

Consultant: Dr. B. Mennesson

Prepared by: Dr. R. Flatscher Date: 21 March 2003

Distribution: See Distribution List

<p>The work described in this report was done under ESA/ESTEC contract. Responsibility for the contents resides in the authors or organisation that prepared it.</p>
--

[illegible]

Issue	Date	Sheet	Description of Change	Release
1	21 March 2003	all	initial issue	

Table of Contents

1	DARWIN BACKGROUND	1
2	ACKNOWLEDGEMENT AND PROJECT TEAM	2
3	DESIGN OF NULLING BREADBOARD	2
3.1	Highly Symmetric Interferometer Architecture	2
3.2	Beam Splitter	3
3.3	Phase Shifter	3
3.4	OPD Control	4
3.5	Star/Planet Simulator	4
4	REALISED BREADBOARD HARDWARE	5
5	PERFORMANCE MEASUREMENTS	7
6	CONCLUSION	10
7	ACRONYMS AND ABBREVIATIONS	10

1 DARWIN BACKGROUND

The European Space Agency is presently studying the Infra Red Space Interferometer Darwin interferometer (formerly known as IRSI) as a cornerstone candidate for the Horizon 2000+ program. This is an instrument with the explicit purpose of detecting other Earth-like worlds, analyse their characteristics, determine the composition of their atmospheres, and assess their capability to sustain life.

The current Darwin configuration is based on six free-flying telescopes arranged in a planar Robin-Laurance architecture providing high star suppression and internal modulation.

At present Darwin is a configuration of 3 Generalised Angel's Crosses (GAC) which are rotated 120 degrees with respect to each other. Each GAC uses one full telescope of the plane hexagon, 4/9 mirror area of the two adjacent telescopes and 1/9 of the mirror area opposite the full telescope. The large and the small telescope are phase adjusted by π relative to the two other telescopes. Darwin will be operated in nulling mode to detect planets and in imaging mode to resolve any extended target with high resolution.

The schematic beam recombination of the Laurance interferometer is shown in Fig. 1-1. The nulled outputs of GAC1 to GAC3 are internally chopped and yield 6 outputs for signal extraction. Switching between the GAC_i signals allows the ac-detection of weak planet signatures out of the masking zodiacal light. The hardware realised in the course of this breadboard contract is marked in red.

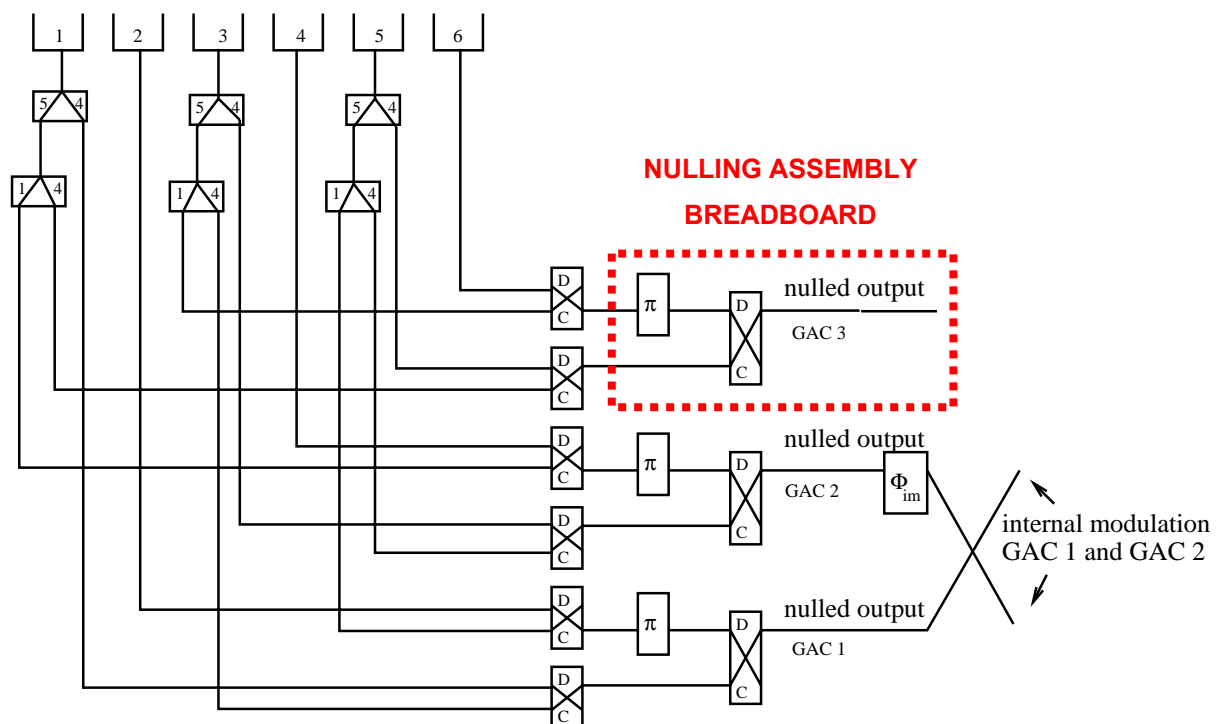


Fig. 1-1: Schematic beam recombination of Robin-Laurance configuration.

2 ACKNOWLEDGEMENT AND PROJECT TEAM

Astrium Germany has been awarded this first breadboarding activity of a nulling interferometer representative for Darwin. The project was sponsored by ESA under ESTEC Contract No. 14827/00/NL/CK and funded by the Technical Research Program (TRP). The project team is composed of Astrium Germany as a prime and TNO/Netherlands, TU-Vienna/Austria, and Layertec/Germany as subcontractors. Considerable internal funding were added by Astrium and TNO to realise the required high-quality hard- and software. The responsibilities of the team members were as follows

- Astrium Germany Prime and system engineering, responsible for system design, concepts selection, optical simulation (ASAP), beam combiner, AIV, and final tests
- TNO-TPD responsible for detailed design and manufacturing of all components except the beam combiner
- TU-Vienna/Prof. Leeb gave support on system level with focus on symmetric beam splitters including FTIR splitter, and wavefront filter, MATLAB simulation of single mode-fibre
- Layertec / Germany manufactured the beam combiner and supplied numerical data for ASAP simulation
- B. Mennesson was a consultant with Darwin system background during the initial study phase

3 DESIGN OF NULLING BREADBOARD

The goal was the design, the manufacturing, and the test of a nulling breadboard representative to the nullers required for the final Darwin instrument. First priority was given to the nulling demonstration of a point source but the imaging of an extended source was demonstrated as well. The breadboard comprises the two-arm interferometer and a star/planet simulator to test the performance. The operating wavelength was in the near infrared 1 to 2 μm range but the design is compatible to fit the Darwin instrument working in the mid infrared between 4 and 20 micron. A star suppression of 50,000 had to be achieved at the short wavelengths to ensure a null depth of 10^{-6} required for Darwin at 10 micron.

3.1 Highly Symmetric Interferometer Architecture

Several interferometer architectures have been investigated and traded with a view to highly symmetric set-ups. The well known Rotational Shearing Interferometer (RSI) was the first concept looked at in detail as extensive experience is available by JPL on this non-planar architecture. The non-symmetric beam combiner requires a compensator plate to become achromatic. Another

interesting approach was the focus transition shift interferometer as proposed by Rabbia. Going through a focus introduces an achromatic phase shift of π but this basic principle may be applied to one interferometer arm only and becomes asymmetric. The finally selected arrangement is based on the well known Michelson configuration with several components added to restore the arm symmetry. It is a planar set-up reducing the manufacturing and alignment effort.

The high nulling quality required for Darwin forces the use of identical components in each interferometer arm. The arrangement of components and the type of beam reflections must be the same. All bulk materials introduce chromatic effects if they are not placed in a symmetric way. The heart of any interferometer is the beam combiner superposing the interferometer beams. It is usually made of a "dispersive" bulk material and coatings applied to one or both sides of the splitter. Utmost symmetry in the beam splitting device is mandatory as a real beam combiner always shows a splitting ratio deviating considerably from the desired 1:1 ratio. We finally chose the auto-balanced Sagnac concept characterised by only one critical beam splitter plate which is passed once in transmission and a second time in reflection. The achromatic design is well suited for Darwin, too.

3.2 Beam Splitter

The beam splitter is the critical part of the interferometer. It must be manufactured of a very homogeneous material with high surface quality. The highly symmetric coating was achieved by rotating the substrate during the sputtering. An uniform coating thickness was realised by adding a linear translation to the substrate during the coating process. We chose a metal splitting layer to obtain a smooth splitting behaviour over the wavelength and to minimise the splitting ripple.

3.3 Phase Shifter

The selected Sagnac core is characterised by a zero phase shift at the achromatic output. The required phase shift of π in a two-arm interferometer must be externally added. Two different phase shifters have been investigated and realised. Both shifters are compatible to Darwin.

The periscope phase shifter (see Fig. 3.3-1 left) uses only metal mirrors and is inherently achromatic in a broad band. The shifter is characterised by a fixed phase shift and a non-planar arrangement. The dispersive phase shifter (see Fig. 3.3-1 right) is Astrium's preferred solution as an additional phase shift of $\pi/2$ is observed at shorter wavelengths. This allows to actively stabilise the OPD control loop at a grey fringe. The principle is fully applicable for Darwin as any bulk material shows a similar dispersive characteristic producing an additional phase shift at shorter wavelengths. The near infrared is preferred for control as the available optical power is higher by 30 dB.

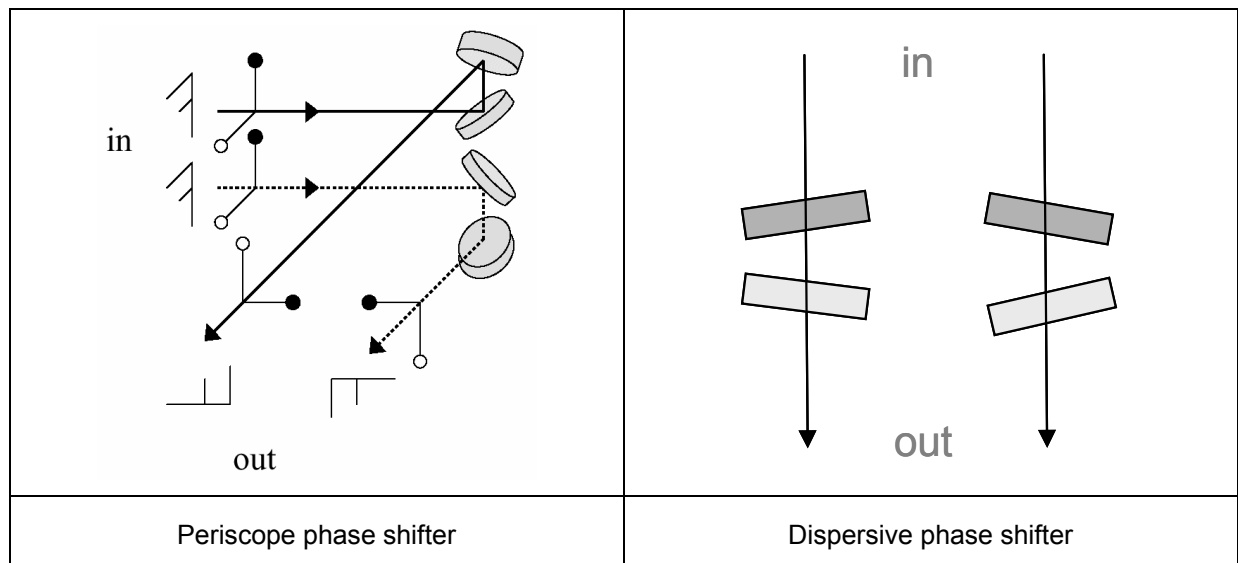


Fig. 3.3-1: Realised phase shifters. Left: Periscope phase shifter for fixed phase shift of π . Right: Dispersive phase shifter system providing perfect phase match at several distinct wavelengths. Arbitrary phase shifts are possible here.

3.4 OPD Control

The control of the interferometer's OPD is performed via a balanced receiver operating at the grey fringe at shorter wavelengths. External and internal OPD fluctuations are corrected. Both interferometer outputs (destructive and constructive) are used to operate in a wide dynamic range. The principle is fully applicable to Darwin relying on a dispersive phase shifter establishing the additional differential phase shift of $\pi/2$ to stable lock on the grey fringe. The chosen OPD control concept combines low effort without wobbling the system's OPD as required for many other approaches.

3.5 Star/Planet Simulator

Two different source simulators have been realised providing two spatially separated point sources each. The wavefront dividing concept picks out two small sub-beams from a collimated and expanded input beam. Beam diameter and baseline can be easily changed by apertures. The second source simulator is based on the amplitude dividing principle. This "improved" simulator provides two perfectly identical and auto-balanced input beams with Gaussian shape. Both realised source simulators are well suited for testing and characterising the breadboarded interferometer.

4 REALISED BREADBOARD HARDWARE

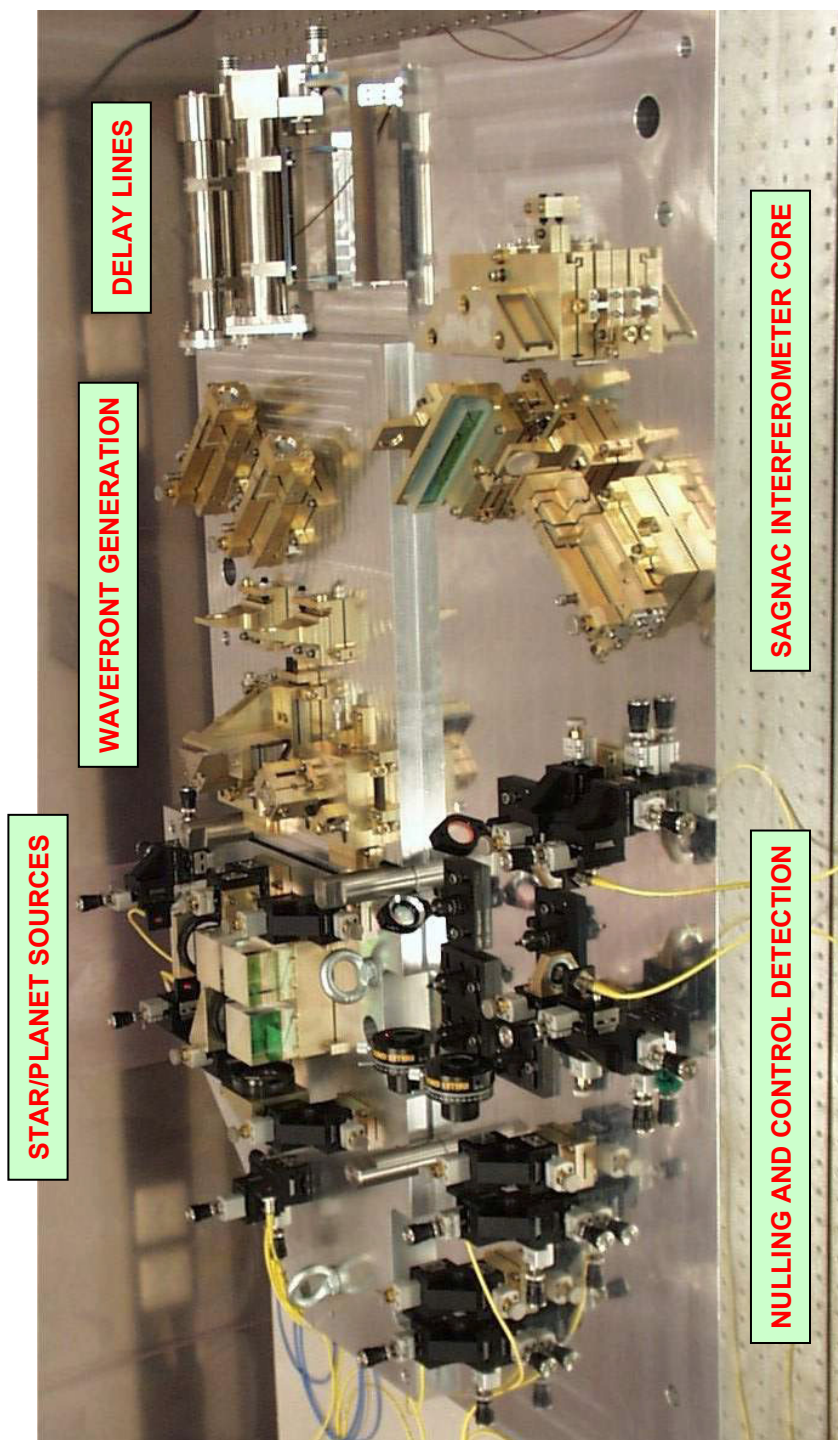


Fig. 4-1: Photograph of realised breadboard hardware with dispersive phase shifter and wavefront dividing source simulator. The set-up is arranged for demonstration of the nulling mode. The noise and turbulence reducing aluminium cover has been removed.

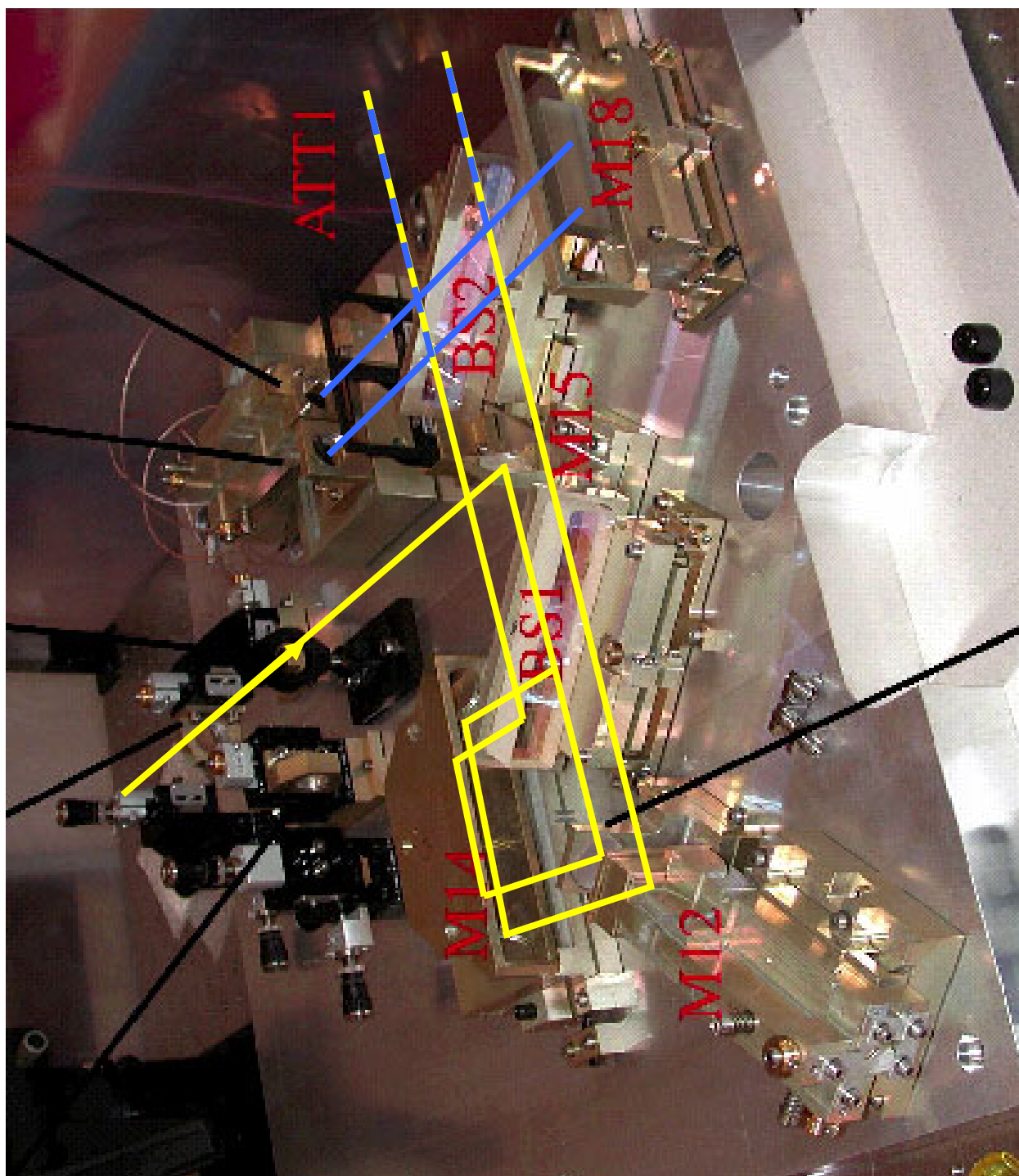


Fig. 4-2: Photograph of improved star/planet simulator based on amplitude division. The same Sagnac core as used in the interferometer generates two input beams auto-balanced in intensity. The star signal is marked in yellow. The added planetary signal is drawn in blue.

5 PERFORMANCE MEASUREMENTS

Excellent results have been achieved operating the interferometer in nulling mode with open and closed OPD control loop. The interferometer is insensitive to the direction of the polarisation. Star suppressions of 408,000 and 91,000 have been measured with polarised diode laser sources of 0.1 nm and 1.5 nm spectral width. Using a broad band ASE source with 30 nm spectral width the best suppression was 36,000 which certainly can be further improved with more careful aligning. The current performance is limited by the atmospheric turbulence of the breadboard environment yielding a typical OPD error of 0.9 nm rms. The maximum allowed OPD error amounts to 2.2 nm if no other error is present in the system.

The next two figures show typical nulling results achieved with different source simulators. The performance of the OPD control loop is characterised by the following two figures.

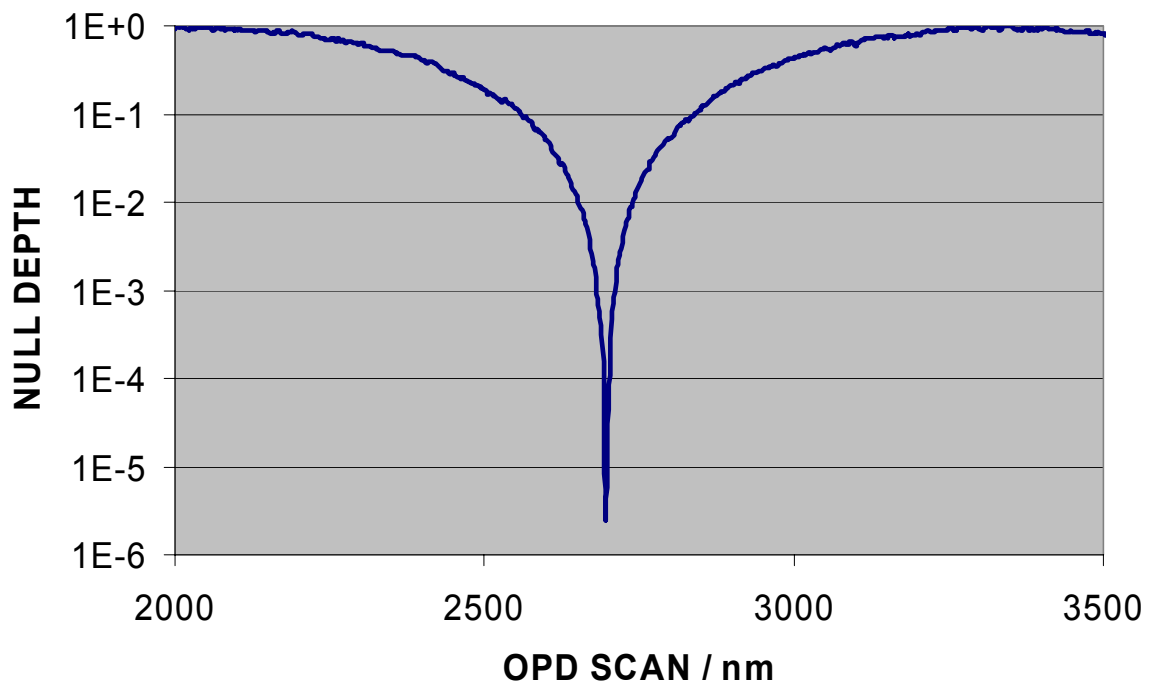


Fig. 5-1: Measured star suppression of 408,000 (goal was 50,000) employing the amplitude dividing source together with the dispersive phase shifter. The star was simulated by the narrow-banded (100 pm) diode laser point source at a wavelength of 1306 nm.

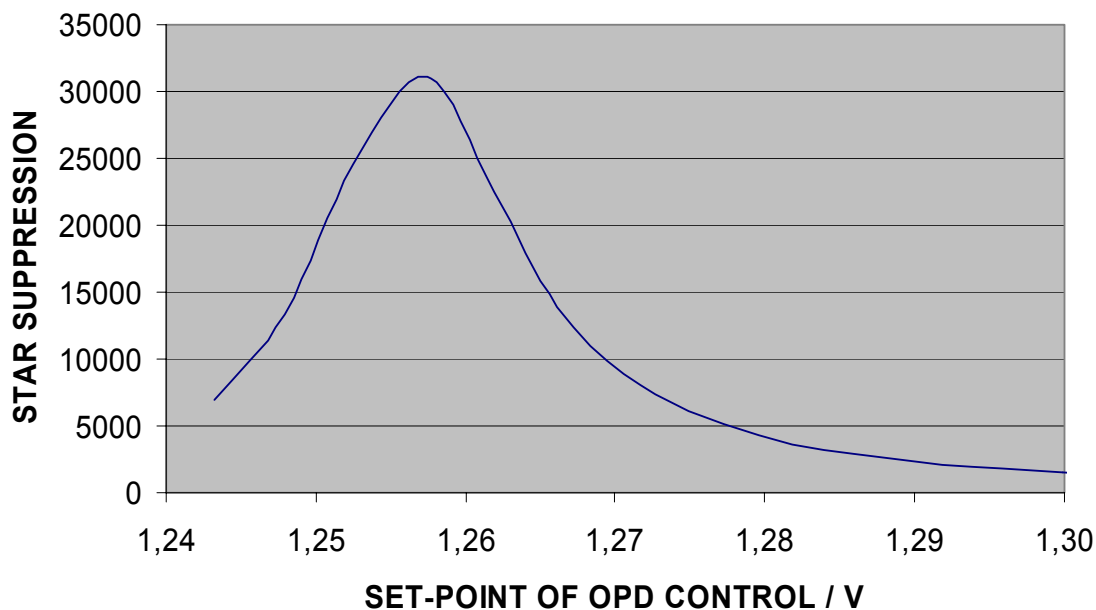


Fig. 5-2: Measured star suppression of 32,000 employing the wavefront dividing source and the dispersive phase shifter. We used a non-polarised broad band ASE laser source emitting in a wavelength range of 1530 to 1560 nm (linewidth of 30 nm) to simulate a star. The best result achieved once was a suppression of 36,000. The set-point of the OPD control has been varied to match the dispersive phase shifter to the ASE linewidth.

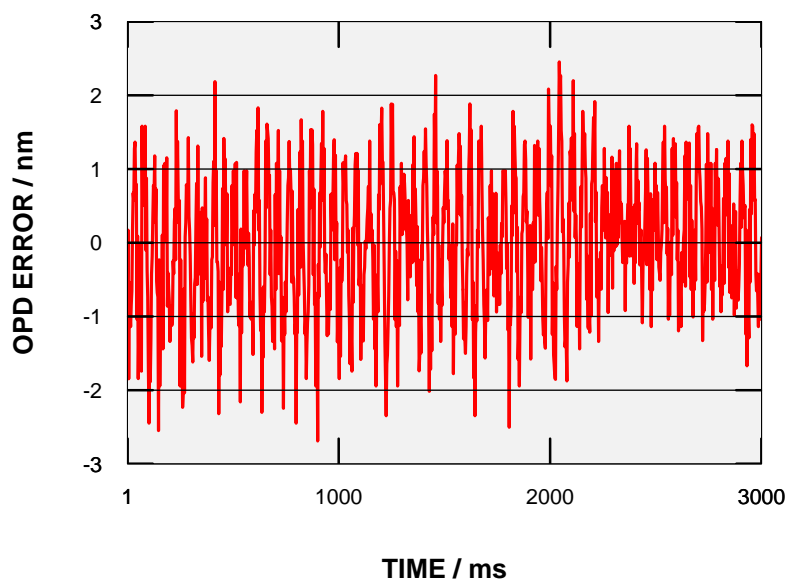


Fig. 5-3: Measured OPD error for closed loop operation. The remaining rms-error amounts to 0.9 nm which is well below the maximum allowed error of 2.2 nm in the near infrared.

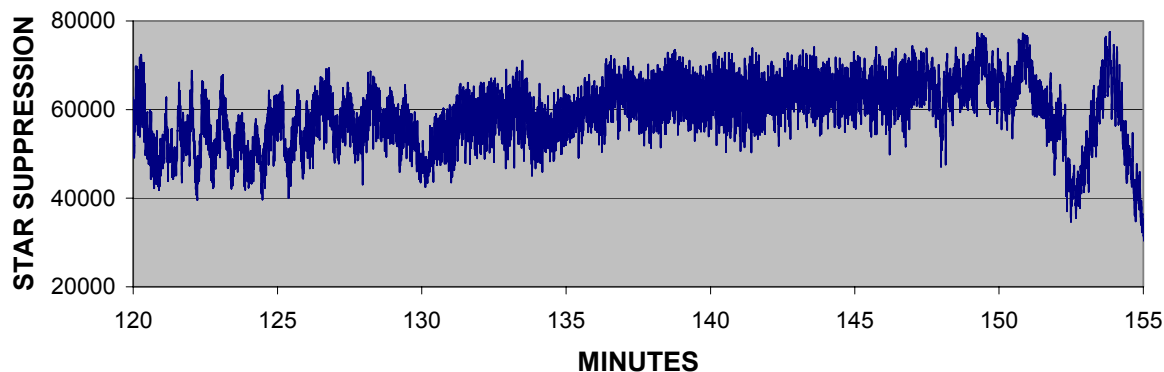


Fig. 5-4: Long-time measurement of the star suppression showing the reasonable working of the OPD control. We used the wavefront dividing source, the dispersive phase shifter, and the 1550 nm diode laser as a star source with a linewidth of 1.5 nm.

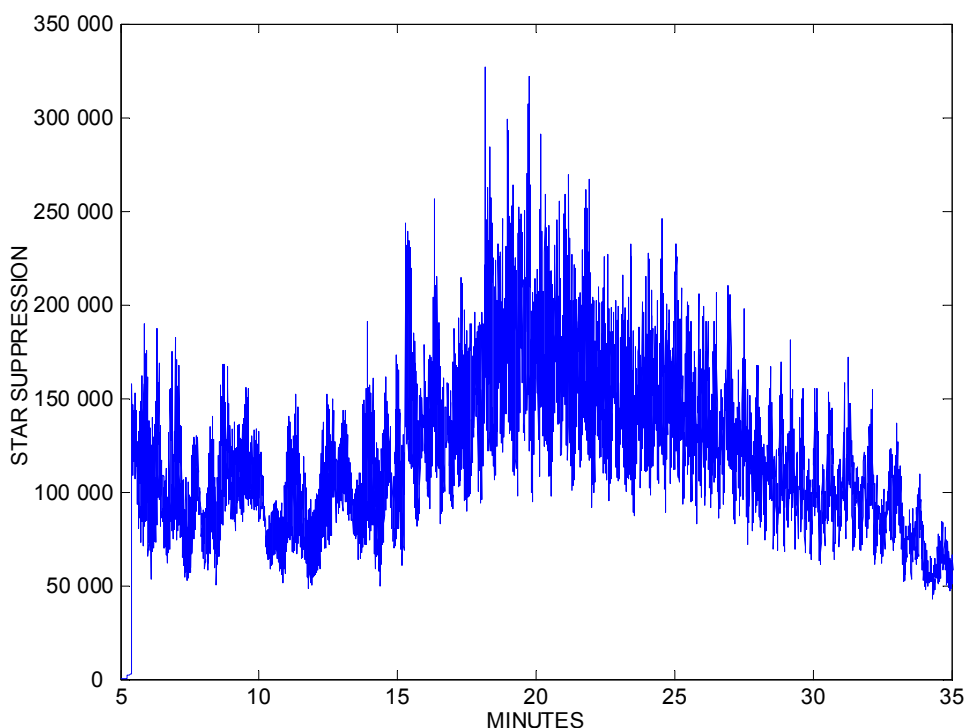


Fig. 5-5: Long-time measurement of the star suppression showing the excellent working of the OPD control. Here, we used the amplitude dividing source, the dispersive phase shifter, and the 1306 nm diode laser as a star source with a linewidth of 100 pm.

6 CONCLUSION

The realised and tested breadboard performed very well confirming the choice of the highly-symmetric interferometer architecture and the involved components and their quality. The used technology is compatible to Darwin and to GENIE as all redirecting elements are made of metallic mirrors working well up to the mid infrared. The central beam splitter needs only a bulk material transparent in the wavelength range of interest, e.g. fused silica in the breadboard or zinc selenid for GENIE/Darwin. The specific splitting ratio and its ripple over the wavelength are not critical due to the chosen double pass architecture. The phase shift of π is established by the dispersive behaviour of any infrared bulk material. Fused silica was used for the breadboard and zinc selenid could be the material for Darwin.

The realised OPD control principle covers external and internal OPD fluctuations and is fully representative for Darwin. It utilises the higher optical power available at shorter wavelength and it does not wobble the OPD around the deep null. No fringe tracker and no internal laser metrology are required.

The breadboard uses a single-mode glass fibre to perform the required wavefront filtering and such fibres are available on the stock in the near infrared. Darwin needs a single-mode waveguide operating between 4 and 20 micron. Astrium recently started the development of such a fibre made of polycrystalline silver halides as no polycrystalline single-mode fibre is available at present. The existing mid infrared glasses are limited in wavelength to the 4-6 micron range.

7 ACRONYMS AND ABBREVIATIONS

AIV	assembly, integration, and verification
ASAP	optic modelling software from Breault Research Organization
ASE	amplified spontaneous emission
Darwin	space infrared interferometer project
ESA	European Space Agency
FTIR	frustrated total internal reflection
GAC	Generalised Angle's Cross
GENIE	Ground-based European Nulling Interferometer Experiment
IRSI	Infrared Space Interferometer
JPL	Jet Propulsion Laboratory
MATLAB	mathematical computing and visualization software
OPD	optical path delay
rms	root mean square
RSI	Rotational Shearing Interferometer
TRP	Technical Research Program
TU-Vienna	Technical University of Vienna