DARWIN FRINGE SENSOR (DWARF): CONCEPT STUDY

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ABSTRACT

The **D**ar**W**in **A**st**R**onomical **F**ringe sensor (DWARF) is one of the most critical components of DARWIN. DWARF's main goal is to measure all the optical path differences from the observed star down to the detector, induced by relative displacements of the 7 free flyers, by vibrations or by thermal effects, in order to enable their correction by delay lines. In the current error budget, nanometric accuracies are required to reach a sufficient null. DWARF must also measure tip/tilt, defocus, astigmatism and coma.

The goal of the study presented here is to identify the best concept for DWARF within the DARWIN environment. Main issues are the selection of the spectral domain from the target list, the merging of a wavefront sensor and an interferometer taking into account the number of beams, the acquisition procedure and space constraints. This leads to a simple and innovative concept. A preliminary DWARF performance is estimated by simulation. In addition, a laboratory breadboard will be manufactured in order to test experimentally the most critical points, as detailed in another paper of this conference "DARWIN fringe sensor (DWARF): breadboard development" by E. Schmidt et al.

Key words: Interferometry; Phase measurement; Wavefront sensing; Space optics.

1. DWARF WITHIN THE DARWIN MISSION

DARWIN/IRSI is a future ESA mission with critical requirements [1]. A previous study by Alcatel [2] derived a conceptual design of the instrument, demonstrating the mission feasibility. One of the identified critical components is the fringe sensor (FS), whose aim is to measure the optical disturbances between the arms of the instrument.

The study presented here summarizes the selection of the best concept for the DARWIN FS (DWARF), taking into account all the specific aspects of the DARWIN context, and the identification of critical aspects in order to test them on a breadboard. This work is the first task of an ESA contract to Kayser-Threde (KT), and has been mainly performed at ONERA with inputs from KT, IMT and Alcatel Space.

2. ANALYSIS OF THE SPECIFICATIONS

The main specifications given by ESA are listed in Table 1. The target stars are given in [3], and the light below 4 µm, not used by the nuller, is allocated to DWARF. Modes to be measured are Optical Path Difference (OPD, Z_1), tip/tilt (Z_2, Z_3), defocus (Z_4) and High order Aberrations (HA, $Z_5..Z_{10}$), following Noll numbering for Zernike modes Z_i [4]. DWARF must measure the absolute tip/tilt value for efficient coupling into the nuller fibers, but only the differential value may be enough for HA as this value is just used as a monitoring tool of fiber coupling. The breadboard will be limited to 2 beams, but operation with up to 6 beams must be considered for the flight model.

From these specifications, the following guidelines have been considered in the design:

- The measurement of high-order aberrations requires an interferometer and a Wave-Front Sensor (WFS);
- The visible domain is the most efficient, even for M-type stars because it maximizes the figure of merit $N(\lambda)/\lambda^2$ where N is the number of photo-electrons. This ratio results from the fact that the OPD noise is proportional to λ/ρ where the signal-to-noise ratio ρ is roughly the square root of the number of photo-electrons N [5]. Even for the coldest stars, the efficiency of photons above 2.4 µm is only a few percents of the total efficiency;
- A very wide magnitude range is requested, and thus the spectral band should be maximized for operation

Table 1. ESA input specifications.

Parameter	Specification
Temperature	40 K
Target spectral type	G, K, M
m_V range	0—12
Wavelength λ	$\in$[0.4,4] µm
Modes to measure	Z_1 to Z_{10}
OPD range (WFE rms)	10 µm
OPD accuracy (WFE rms)	0.75 nm
Tip-tilt range (WFE rms)	18 µm
Tip-tilt accuracy (WFE rms)	1.21 nm
Beam diameter	20 mm

on the faintest stars;

- The most critical specifications are OPD and tip/tilt repeatability (closed-loop operation);
- DWARF should include redundancy and no moving parts;
- Dichroic plates are best suited to split beams (for example, between the interferometer and the WFS, for redundancy) since they maximize the flux in a given spectral band;
- Open loop is required for fringe acquisition (OPD and tip/tilt), with a large dynamic range.

In addition, some spectral resolution is required since the star may be resolved by the baseline at the shortest wavelengths. Therefore, when several detectors are required (for different functions in the sensor or redundancy). Feeding them with dichroic plates provides some (limited) spectral resolution for free.

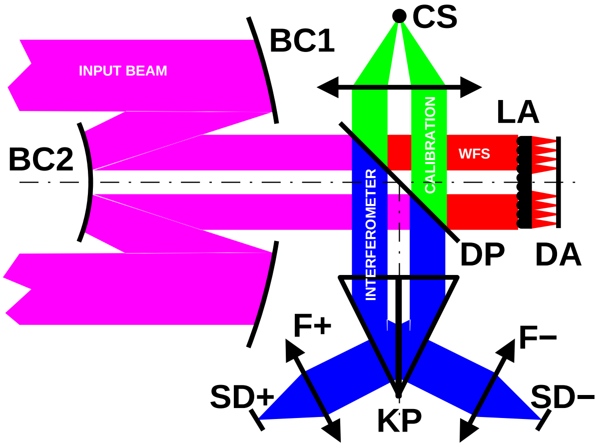
Another key point is that space nulling missions are very complex. Minimizing DWARF complexity is thus an important system driver [6].

3. THREE POSSIBLE SOLUTIONS FOR DWARF

The following sections describe three implementations for a 2 beam DWARF. Extension to 6 beams can be performed for example by splitting each beam in two, to feed 6 FS with 1+2, 2+3, 3+4, 4+5, 5+6 and 6+1 pairs.

3.1. Concept ❶: Pupil-plane coaxial single-pixel interferometer+WFS

For a closed-loop OPD tracker, the best solution is to monitor the flux difference between the two inflection points (grey fringes) of an interferogram [7]. This algorithm is sometimes referred to as the "AC" algorithm, from the classical "ABCD" algorithm [8]. This solution can be simply implemented using the two phase-opposite outputs of a coaxial beam-combiner, such as a Köster prism (KP) for perfect symmetry (Fig. 1) and can use efficient single-pixel detectors such as avalanche photodiodes. The routing scheme between the beams and the FSs must consider that Köster prisms must be fed by only one polarization. To measure high order modes, a WFS such as a Hartmann-Shack can be used. The beam compressor reimages the two pupils on the lenslet array (4x4 grid per pupil to correctly sample the highest frequencies) with a diameter similar to the detector array. The reduced real pupil is also used by the KP.



BC1+BC2:Beam Compressor ; LA:Lenslet Array ; DA:Detector Array ; CS:Calib. Source ; DP:Dichroic Plate ; KP:Koster Prism ; $SD_{\pm}$:Single-pixel Detector.

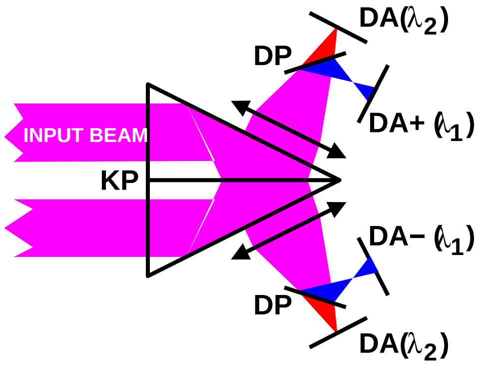
Figure 1. Concept ❶: Monomode Interferometer + Wave-Front Sensor.

3.2. Concept ❷: Pupil-plane coaxial multiple-pixel interferometer

To simplify Concept ❶, the WFS can be included in the interferometer since a 2D detector can sample the OPD in the pupil, for example on a 4x4 grid (Fig. 2). In this case, only the differential aberrations between the two beams can be estimated, and only when fringes are present. For large-amplitude or absolute tip/tilt measurements, a focal-plane detector is required to replace the Hartmann-Shack detector. This can be achieved by a dedicated device for each telescope (telescope and focal plane detector), or by using the same telescope and a focal-plane detector in a spectral domain where KP mainly reflects or transmits.

3.3. Concept ❸: Focal-plane multiaxial interferometer

Another approach is to use a focal-plane combination (Fig. 3). The image is then the combination of the two images coming from each pupil, modulated by Young fringes. The OPD can be derived from the phase of these fringes. The other modes can be derived from the shape of the image. Unfortunately, this phase-retrieval approach does not allow to fully derive the phase on each pupil [9]. For example, if the two images shift apart, there is no way to know which beam goes in which direction. To solve for the sign ambiguity on even modes, a solution



KP:Koster Prism ; DP: Dichroic Plate ; $DA_{\pm}$: Detector Array ; DA: tip/tilt Detector Array.

Figure 2. Concept ❷: Multimode Interferometer.

is phase diversity. It consists in recording another image, with a known aberration. The simplest and most used phase diversity is a defocus, obtained by slightly shifting the detector [10, 11]. Since the object is known for all wavelengths, the two images can be produced by a dichroic plate near the focus, which allows to maximize the number of photons in a given spectral bandwidth. In this case, the diversity of the transmitted beam is the defocus plus the aberrations introduced by the plate. Phase diversity has been validated recently for multiple-aperture systems, numerically [12, 13] and experimentally [12].

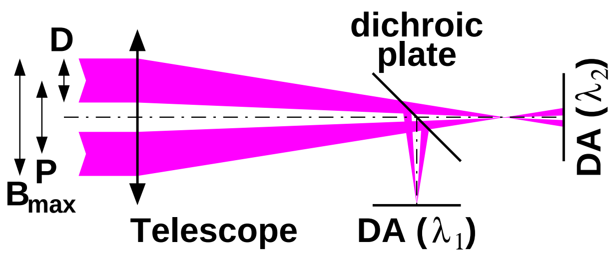


Figure 3. Concept ❸: Focal-plane interferometer.

With Concept ❸, the resolution in the pupil is given by the width of the focal-plane image processed. A small width is used for OPD estimation, to minimize real-time processing and noise from pixels with low illumination, while a larger support can be used for high-order modes since real-time operation is not required and RON on long-exposure images is reduced by averaging.

4. TRADE-OFF ELEMENTS

A numerical simulation has been performed to compare these three concepts. Fig. 4 shows the repeatability for OPD measurements, in the case of a 6 beam sensor operated on an unresolved star. If N denotes the number of photons per beam, then with a pairwise scheme (6 FS fed by pairs 1+2, 2+3, 3+4, 4+5, 5+6 and 6+1) each of the 6 FS in parallel is fed by N photons since there are two beams per FS and two FS to feed for each beam. For all the concepts, performance is defined as the OPD standard deviation on the worst baseline (opposite pupils for Concept ❶ and Concept ❷). For this simulation, a 1.5 dilution ratio (defined as the separation of the pupil divided by their diameter [14]) has been chosen in Concept ❸, and the only difference between Concept ❶ and Concept ❷ is the number of pixels used. This is evidenced by the location of the photon-noise (smallest slope) and detector-noise (steepest slope) regimes. Fig. 4 shows that coaxial pupil-plane sensors are slightly more efficient than multiaxial focal-plane sensors. In the photon-noise regime, Concept ❸ is worse than Concept ❶ or Concept ❷ because the two coaxial concepts use the optimum AC algorithm, whereas the multiaxial concept is based on an ABCD modulation.

Fig. 4 shows that the limiting V magnitude is 12.2 for Concept ❶, 11.8 for Concept ❷ and 11.3 for Concept ❸. It is thus possible by increasing the bandwith to reach the specifications for all stars in the magnitude range. Increasing the bandwidth will shift the curves horizontally, which means that the detector cut-off magnitude will still be under the limiting magnitude for Concept ❷. Performance can thus be increased by using low-RON detectors currently under development.

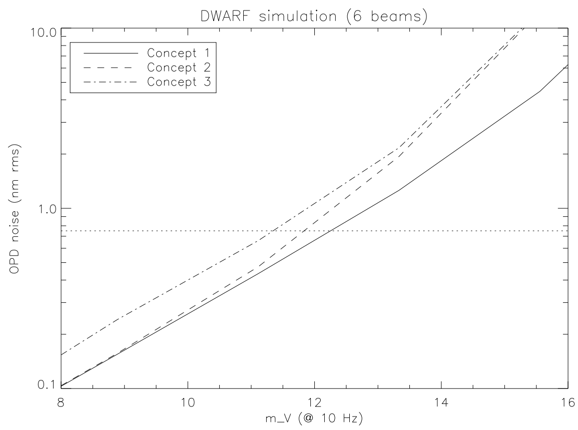


Figure 4. Simulated performance of the three setups. The dotted line is the specification. All the photons available in the V band (λ= 0.55 μm, $\Delta\lambda$ = 0.089 μm)) have been used (targets are characterized by their V magnitude).

In addition, the following items must be considered in the comparison:

- The main drawback of coaxial sensors is that a focal-plane is also required, for the Shack-Hartmann WFS (Concept ❶) or for large/global tip/tilt measurement (Concept ❷). These devices thus have an important complexity induced by the number of detectors;
- Noise estimation for a Shack-Hartmann WFS (including the 4-cell tip/tilt sensor) shows that a significant number of photons is required to have a similar limiting magnitude for the OPD and tip/tilt sensors [15]. Therefore, OPD measurement performance of Concept ❶ and Concept ❷ is reduced by the photon sharing with tip/tilt, not considered in this simulation, whereas for Concept ❸, all the photons are used for all the measured modes;

- These concepts can be extrapolated to a larger bandwidth than the V band used to derive Fig. 4. As mentioned previously, the use of most of the allocated band (from 0.4 to 2.4 μm) is required to reach the specified performance for the faintest stars. This is not an issue for Concept ❸ since different detectors can be fed by a dichroic plate near the focus. In the case of Concept ❶ and Concept ❷, the maximum bandwidth may be limited by the coatings (beam splitter, anti-reflection coating).

Therefore, the small difference in the magnitude limit disappears when considering simultaneous tip/tilt measurement and system complexity. For DWARF, we propose to use a single combining telescope (Concept ❸), and to feed several detectors by dichroic plates to implement phase diversity and redundancy with the largest spectral band.

5. CONCLUSION

The analysis performed has shown that the concept selected for DWARF meets all the ESA requirements. It is based on a focal-plane combination (Concept ❸), as it allows to merge the OPD and wave-front sensors in a common and very simple device, which can be easily fed by 6 beams and a large spectral band. DWARF will be operated in the visible, which is the most efficient spectral domain, and IR can be used in parallel, to increase performance on coldest stars by maximizing the bandwidth, or for redundancy.

The next steps are the the detailed design, manufacturing and test of a breadboard, as detailed in the companion paper [16].

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6. ACKNOWLEDGEMENT

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