Mission Objectives

- Find and characterise other Earths orbiting other stars
- Provide unique imaging capability for general astrophysics

The need for nulling interferometry

- The problem
Comparison of stellar & planetary signals

Earth + Sun at 10 pc, l = 10 mm, l/Dl = 20

<table>
<thead>
<tr>
<th></th>
<th>( e^{-s^{-1} channel^{-1}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planet</td>
<td>0.14</td>
</tr>
<tr>
<td>Solar Zodi</td>
<td>140</td>
</tr>
<tr>
<td>Exo-Zodi</td>
<td>45</td>
</tr>
<tr>
<td>Stellar leaks</td>
<td>( 30 \times 10^5 / \rho )</td>
</tr>
</tbody>
</table>

⇒ background noise must be controlled

But, how do you get the null ???
Bracewell : 2 pupils

![Diagram of Bracewell: 2 pupils](image1)

Other nulling configurations

<table>
<thead>
<tr>
<th>Concept</th>
<th>Bracewell</th>
<th>Angel's Cross</th>
<th>5-telescope &quot;Darwin&quot;</th>
<th>Single DAC</th>
<th>Mariotti (monoplane)</th>
<th>OASES</th>
<th>Modified Mariotti (multiplane / hub)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristics</td>
<td></td>
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<tr>
<td>Rej. Law</td>
<td>$\theta^2$</td>
<td>$\theta^4$</td>
<td>$\theta^4$</td>
<td>$\theta^4$</td>
<td>$\theta^4$</td>
<td></td>
<td>$\theta^4$</td>
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<tr>
<td>Achromatic Phase delay</td>
<td>$\pi$</td>
<td>$\pi$</td>
<td>$2\pi/5$</td>
<td>$\pi$</td>
<td>$\pi$</td>
<td>$\pi$</td>
<td>$\pi$</td>
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<tr>
<td>Symmetric background rejection?</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Planet signal modulation</td>
<td>Rotation of interferometer</td>
<td>Rotation of interferometer</td>
<td>Rotation of interferometer</td>
<td>Rotation of interferometer</td>
<td>Internal modulation</td>
<td>Rotation of interferometer</td>
<td>Internal modulation</td>
</tr>
<tr>
<td>Beam combination complexity</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>AOCS complexity</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>5</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Long delay lines?</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>Shorttime delay lines?</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Imaging mode difficulty?</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>
3-GAC nulling interferometer

- Hexagonal configuration of 6 telescopes
- Central hub / beam combiner
- Only integral $\pi$ phase shifts needed...
  - unequal amplitude sharing (1/3, 2/3, 3/3)
- Internal modulation

GAC : Fresnel vector diagram

Single GAC

$A_1 = A$

$A_2 = A_4 = \frac{1}{3} \cdot A$

$A_3 = \frac{1}{3} \cdot A$

$A$ (amplitude of a full pupil)
Beam Combination (3)

Transmission map & nulling

Alcatel Space

local ZL + other background signals

exo - ZL planet

Stellar disk

On-axis null

4 rejection law

Residual stellar leakage

Detected ZL & other background flux

Planet signal

Field Stop
### Connected Structure?

<table>
<thead>
<tr>
<th>Free Flyer</th>
<th>Connected structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable baseline (≤ 1 km)</td>
<td>Fixed baseline (≤ 100 m?)</td>
</tr>
<tr>
<td>2D / 3D configurations</td>
<td>Linear configurations</td>
</tr>
<tr>
<td>No mechanical coupling</td>
<td>Low frequency resonance</td>
</tr>
<tr>
<td>High cost</td>
<td>Very high cost</td>
</tr>
<tr>
<td>New technology</td>
<td>Technology available (ISS, SIM)</td>
</tr>
</tbody>
</table>

### Key System Parameters

- Optical nulling of "on axis" star by $\sim 10^5$
- Baseline accuracy : 1 cm
- Optical path difference : 20 nm
- Telescope pointing : 24 mas
- Amplitude matching : $10^{-2}$
**Key System Parameters**

Rejection Ratio for 3-GAC Nulling Interferometer

- **Amplitude matching errors (x 10^-3)**
- **RMS OPD Errors (nm)**

- **Log (Rejection ratio)**

**Technical challenges**

- **Stellar light rejection to ~10^-5**
- **Distinguish between exo-planets and exo-zodi**:
  - rotation of the complete interferometer during observations?
  - internal modulation?
- **Thermal IR observations**:
  - telescopes and structures at ~ 40 °K
  - detectors cooled to ~ 6 °K
- **System complexity**:
  - complex control systems
  - complex beam combining optics
  - redundancy, cost, reliability
Mission constraints

- Launcher: Ariane-5
- Orbital position: L2
- Mission duration: 5 yrs
- Monolithic mirror technology

Telescope Flyers
Propulsion

- Fine control: $\mu$N - thrust
- Coarse control: mN - thrust
- FEEP - Field Emission Electric Propulsion
- Cold gas?

Thermal Control

- Service module: 300 K
- Optics: 40 K
  - planar configuration necessary
- Large deployable sunshields [$r \approx 3.5\ m$]
- Optical bench (non-radial) thermal gradients $< 30\ mK / m$
Communications

- **X-band** ground links
  - Command rate: 4 kbps
  - Telemetry rate: 20 kbps

- **S-band** inter-satellite

- **Emergency S-band** links

Launcher Accommodation

- Beamcombiner
- Telescope flyers
- Upper dispenser
- Master Satellite
- Telescope flyers
- Lower dispenser
Roadmap

Development Phase

2000 Technology development

2004

Definition Phase

2006

Demonstration Flight

2012

Expected detections

Two scenarios:

- 10% stars have telluric planets
- 40% stars have telluric planets

Nb of detections

$\Phi_{tel} = 1.5m$

- Observed stars (if 10%)
- Studied planets (if 10%)
- Observed stars (if 40%)
- Studied planets (if 40%)

Observed stars (if 10%)

Studied planets (if 10%)

Observed stars (if 40%)

Studied planets (if 40%)
– **Major sub-systems**

- **Science telescope**: very fast parabolic primary mirror (F/1), with ultra-lightweight structure, WFE requirement of ~50 nm.
- **WFC**: more detailed analysis needed, to check no major difficulties.
- **Fringe tracker**: design and detailed analysis needed.
- **Flux matching device**: design has been proposed, real life performance yet to be evaluated.

**Optical components**

- Precise manufacturing control of dichroic mirrors, beam-splitters & compensating plates: $10^{-3}$ uniformity in transmission - from one component to any other, at all wavelengths.
- High uniformity of refractive index of thermal IR materials (dispersion $\sim 10^{-3}$).
- Precise control of spectral response (dielectric coatings) in both polarisations, for dioptric components.
- Monomode optical fibres for thermal IR ($6 \sim 18 \mu m$), with suitable homogeneity and good optical throughput. Chromatic requirements TBD.
- Characterisation of nominal performance of the former at 40 K.
- Achromatic Pi phase shifter: differential chromatism $\sim 1$ nm ($\sim \leq 2\pi/1000$ in phase).
Technology development requirements

- FEEP Thrusters - science mode
  - Noise requirement: \( < 1.65 \mu N \) @ 1 Hz.
  - Thrust resolution: \( < 3 \mu N \)
  - Maximum thrust: \( > 50 \mu N \)

- FEEP Thrusters - interferometer reconfiguration
  - Maximum thrust: \( \sim mN \)

- RF ranging & goniometry systems

- Comparative laser metrology system

- Transverse motion sensor

The need to go to space versus ground based development

- Nulling demonstration in lab and at VLTI

- Fringe detection in space is a key element of the precursor mission
  - Fringe detection is an integral part of the control loop for formation flying
Precursor flight

- DARWIN launch in 2014 requires technology readiness by 2007
  ⇒ SMART-2 precursor mission
- DARWIN technology demonstration will also benefit other programs such as XEUS and LISA

Precursor flight technologies

- Interferometry constellation control (formation flying)
- Deployment Control
- Formation Flying RF subsystem
- High Precision Optical Metrology
- milli- and µ-Newton propulsion technology
- Acquisition of interferometric fringes
International collaboration

Close co-operation exists at the scientific level between ESA and NASA on DARWIN and TPF

Conclusions

• We have completed - the first ever - system level feasibility study of an interferometric observatory in space
• The mission can achieve its scientific objectives
• DARWIN is feasible and can be carried out in a time frame consistent with ESA's Horizon 2000+ program
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