# Design, performance, and limitations of the Field Reversal APS

Nulltimate
Final Report
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ESA-ESTEC

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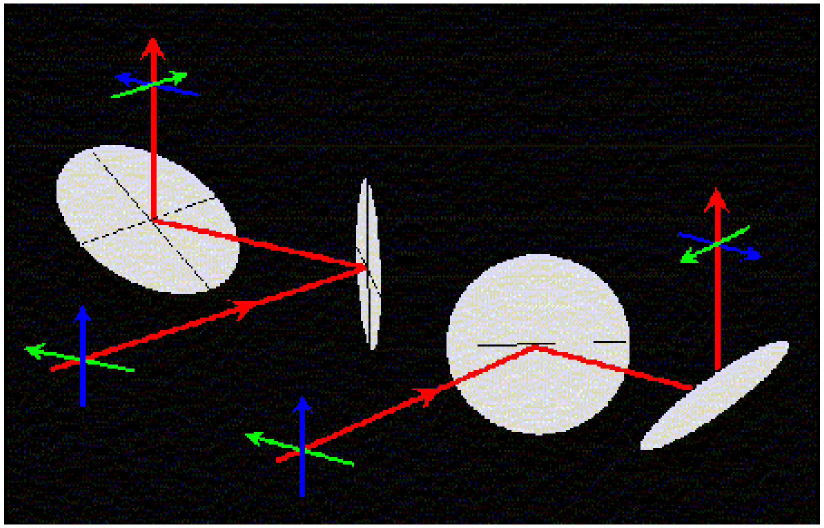
# FR-APS

## Outline:

1. Working principle
2. Involved Institutions and People
3. History
4. Specifications and Performance of Breadboard
5. Advantages and Intrinsic Limitations of the FR-APS for Nulling Interferometry
6. Conclusions

# Principle

- Geometrical pupil flip = reversal of electric field = π phase jump
- A pair of mirror-symmetric right-angle periscopes (two reflections on flat mirrors in each arm) yields a relative 180º rotation of both the input fields and the apertures
- Same principle as focus crossing, but with two successive 1-D flips instead of one 2-D flip



# FR APS

## Instutions and people involved

- ESA
- IAS
- MPIA, Heidelberg (*R. Launhardt, O. Chesneau, D. Butler*)

  => Lead in all phases, characterization measurements

- Kayser-Threde GmbH, Munich (*E. Schmidt, M. Erdmann, T. Stuffler*)

  => Modeling, assessment, design

- Fraunhofer Institute for Applied Optics, Jena (*E. Beckert, G. Harnisch*)

  => Manufacturing of breadboard device

# FR APS

## History

- 2001: Method developed in parallel at JPL and EADS-Astrium, published first by Serabyn and Colavita (Appl. Optcis, 40, 1668)
- 2002: Phase-Shifter Study for Darwin Nulling Interferometer (Nulltimate Project)
- 2003, Phase 1: Assessment and modelling (**KT** & MPIA)
- 2005, Phase 2a: Manufacturing of Breadboard device (MPIA & **IOF**)
- 2006, Phase 2b: Characterization measurements (**MPIA**)
- 2006: KIN reaches in Lab nb 10000:1, wb 5000:1, and on sky repeatable 100:1 nulls
- 2007: TPF nulling breadboard at JPL reaches $10^{-6}$ rejection monochromatic and $2\ 10^{-5}$ with 20% bandwidth. JPL testbed terminated.
- 2007: FR-APS Hardware and breadboarding report delivered to IAS

# FR APS

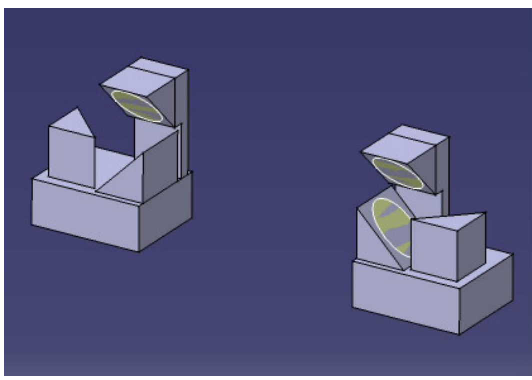
## Breadboard Device

**WP 3120 Final Report** by MPIA Heidelberg, November 2006

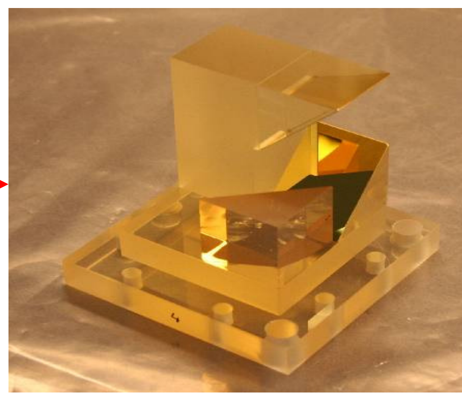
R. Launhardt, D. Butler, O. Chesneau

Manufactured by Fraunhofer IOF Jena, Dept. for micro-positioning

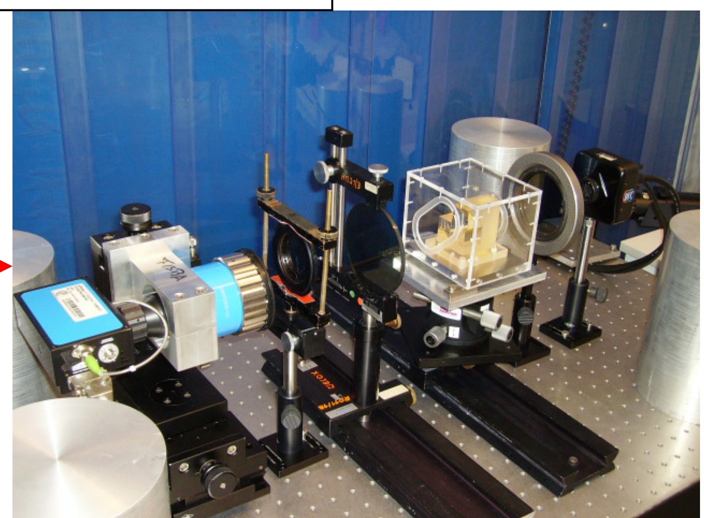
- Zerodur prisms and baseplate
- Flat polished surfaces
- Molecular adhesion bonding with *highest possible angular acuracy*
- Reflective surfaces: 240 nm sputtered Au, unprotected



KT Model



IOF device



MPIA measurement setup

# FR APS

## Specifications and Characterization of FR APS

| Item | Spec | Measurement | | Comment |
|---|---|---|---|---|
| | | FR-APS1 | FR-APS2 | |
| WFE RMS [l=0.63mm, $f_{beam}$=15mm] | ≤30 nm | 39 nm | 45 nm | (OK)<br>(Slightly out of spec, but acceptable with spatial filtering) |
| Introduced beam tilt | <20arcsec | <15arcsec | <15arsec | OK* (next slide)<br>(all mirrors within 8 arcsec to nominal orientation) |
| Polarization rotation | <0.5deg | Compatible with model | Compatible with model | (OK)<br>Could not be measured with required accuracy.<br>By assessment well within spec |
| Flatness of polished back-surfaces | <60nm | <9 nm | <9 nm | OK<br>(only needed for alignment) |

# FR APS

## Beam tilt introduced by the FR APS units

- The beam tilt (out – in) depends on the alignment of the APS units with the incoming beam axis
- Specified and polished reference surfaces at prism sides are used for alignment
- For „perfect“ alignment of the as-built APS units, the introduced beam tilt is < 10 arcsec
- Beam tilt is < 15 arcsec as long as the reference surface is aligned to better than ±5 arcsec with the incoming beam

# FR APS

## Expected Performance as Phase Shifter

The as-built device is expected to provide a stable on-axis 180º (π) phase shift and better $10^{-6}$ null between two afocal beams of 15mm diameter ***if***:

- Vibrations and mechanical drifts are under control
- Incoming beams are afocal (divergence <±0.7º) and fully symmetric in terms of intensity and polarization
- APS reference surfaces are aligned to incoming beam to better ±5"
- Incoming beam coherence > $1\ldots2\times10^{-6}$ ( 0.999998) **over the full pupil size**
- The beam combiner is fully symmeric and preserves the polarization symmetry


# FR APS

## Advantages of the FR-APS design

- Simple principle and simple realization
- Feasible with current technology for reasonable price
- Intrinsically achromatic, i.e., suited for broad-band MIR
- Full symmetry between the two arms
- No powered optics
- No control loops or fine tuning
- Phase shift and beam combination are separated
- Potentially space-qualified

# FR APS

## Limitations and drawbacks for stellar nulling and exoplanet observations

- Fixed π phase shift, not adjustable, limits application range and requires other phase shifter if adjustments are necessary
- Very strict requirements on coherence, polarization symmetry, and beam combiner may push the price of the periphery
- Testbench issue: vertical beam displacement
- Consequence of pupil / FoV flip: sky regions covered by the refracted beams of the two telescopes overlap only partially. The result is a **reduced interferometric FoV** and **fringe contrast loss**, i.e., significantly **reduced transmission** and decreased SNR in white fringe where the planet is (see Hénault 2006)
- Transmission losses may still be less severe than for transmissive APS

# FR APS

## Conclusions

- The breadboard device was built with the highest accuracy (surfaces & alignment of bonded surfaces) that is currently possible
- The breadboard device complies with all specs that should enable it to provide a broad-band Null $<10^{-6}$, *if* beam combiner and periphery comply with all their specs
- The predicted performance has not been tested on a cryogenic nulling test bench
- Since JPL also failed to reach good nulling with FR APS (reason remains unknown), the practical nulling performance remains unproven