Modal noise mitigation in few-mode fibers

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CONTEXT

- **NIRPS** (**N**ear **I**nfra**R**ed **P**lanet **S**earcher) is an AO-assisted fiber-fed RV NIR spectrograph for La Silla
- YJH-band RV spectroscopy focusing on rocky planets around M-stars
  - 1 m/s radial velocity precision
  - Planetary atmospheres characterization
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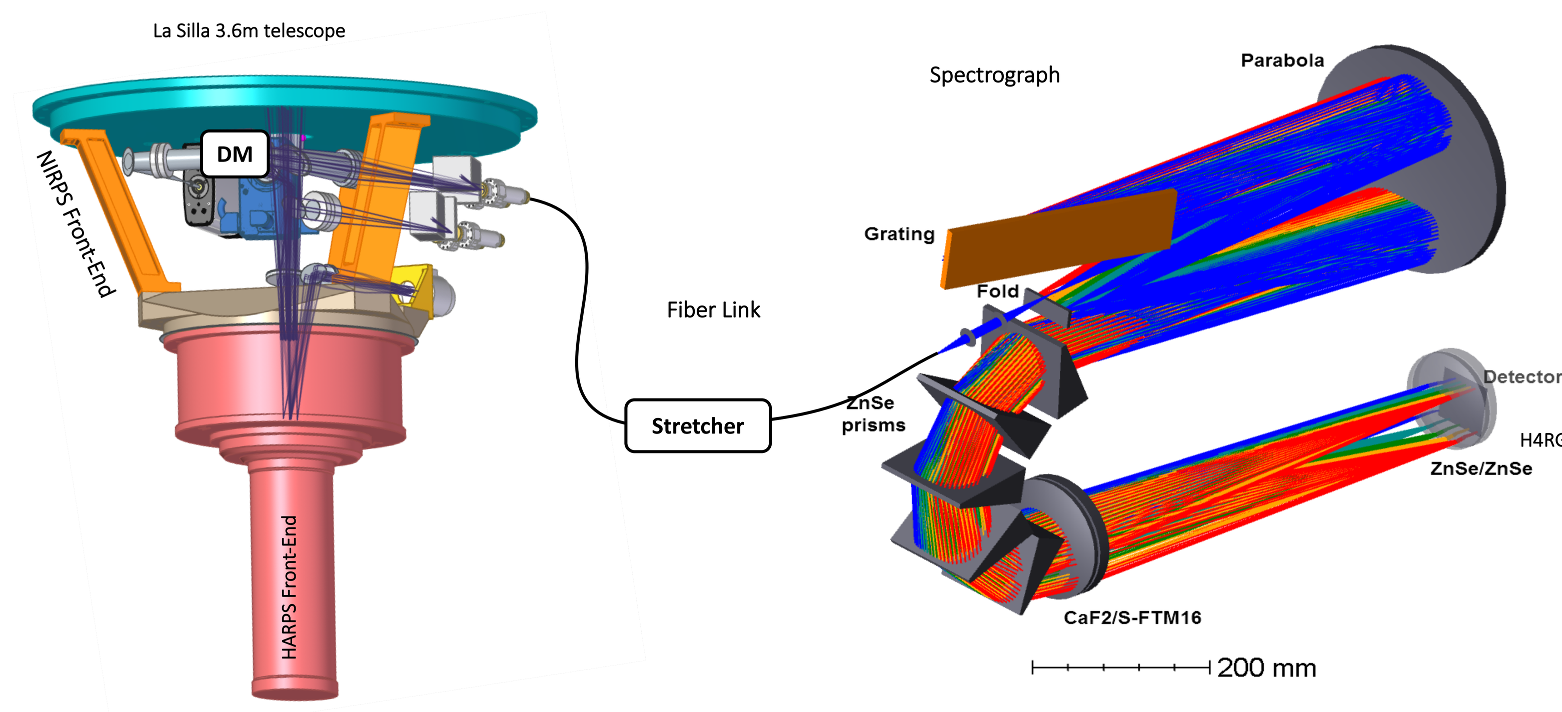
Mode	Fiber at telescope	Fiber at spectrograph	R
AO with 0.4" fiber	OCT 29μm	OCT 29μm	100.000
Seeing-limited with 0.9" fiber	OCT 66μm	RECT 33x132μm	75.000

- Simultaneous observations with HARPS
- First light end of 2019



COUPLING EFFICIENCY

Blind+, 2017 (AO4ELT)

Thanks to the AO system, star light is coupled to an 0.4" fiber with high coupling efficiency

- ➢ Coupling efficiency can outperform seeing-limited instrument by 30 to 50% (*Fig. 1*)
- ➢ Gain of 1-2 magnitude over single-mode solution

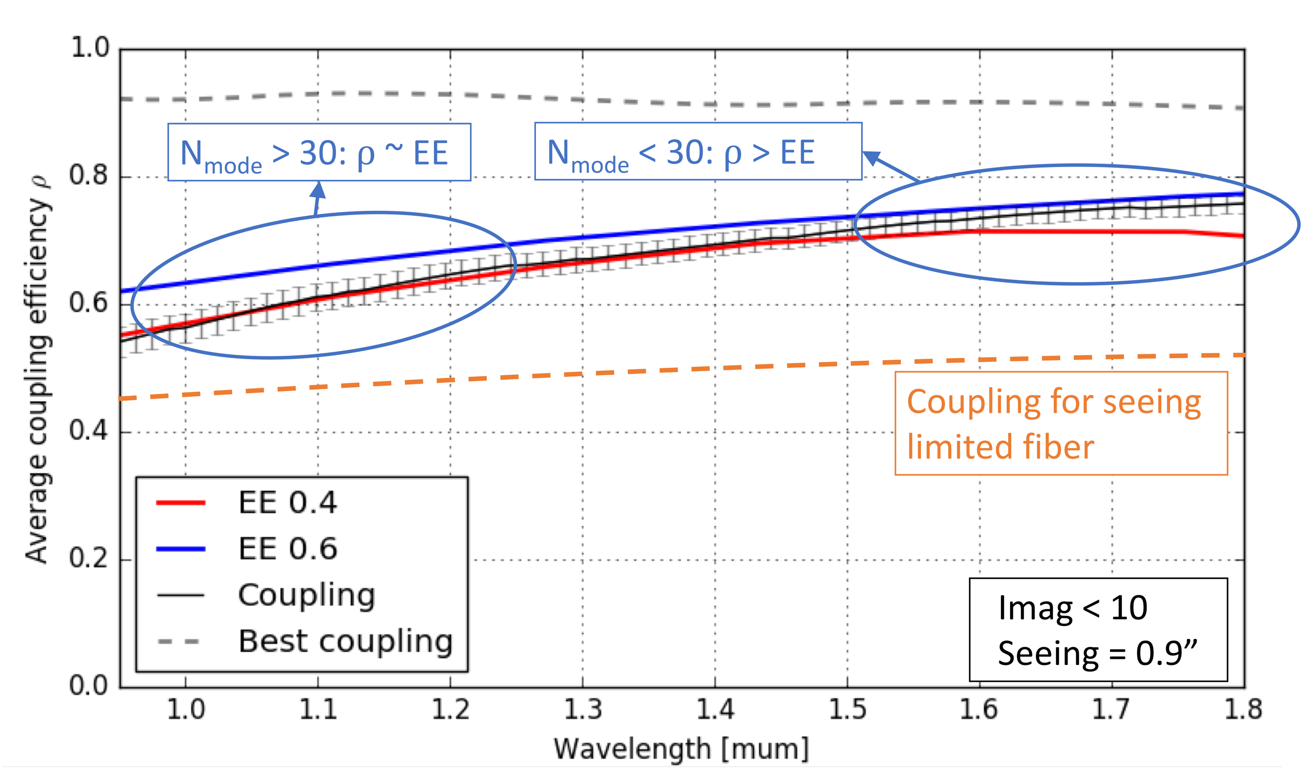


Fig. 1 - NIRPS coupling efficiency in standard median conditions

MODAL NOISE IN FEW-MODE FIBERS

- 0.4" fiber in YJH bands means 10 to 50 modes are guided (vs 1000s for HARPS)
- **NIRPS fibers work in the few-mode regime**
  - ➢ Ray tracing does not apply anymore!!! (Fig. 2)
- Modal noise: variation of fiber output illumination, caused by changing input illumination condition (e.g. tracking error) or external factors (e.g. temperature)
- Modes well separated: low scrambling efficiency and high modal noise , ~20 times higher than for HARPS (Fig. 3)

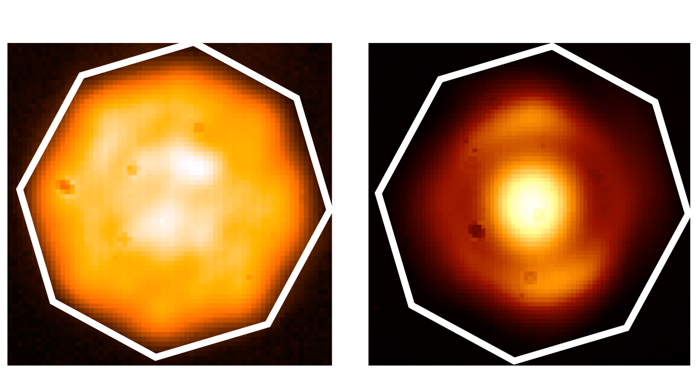


Fig. 2 - Near-field of 50-mode (λ=950nm) and 15-mode (λ=1650nm) octagonal fiber when injecting in core center.

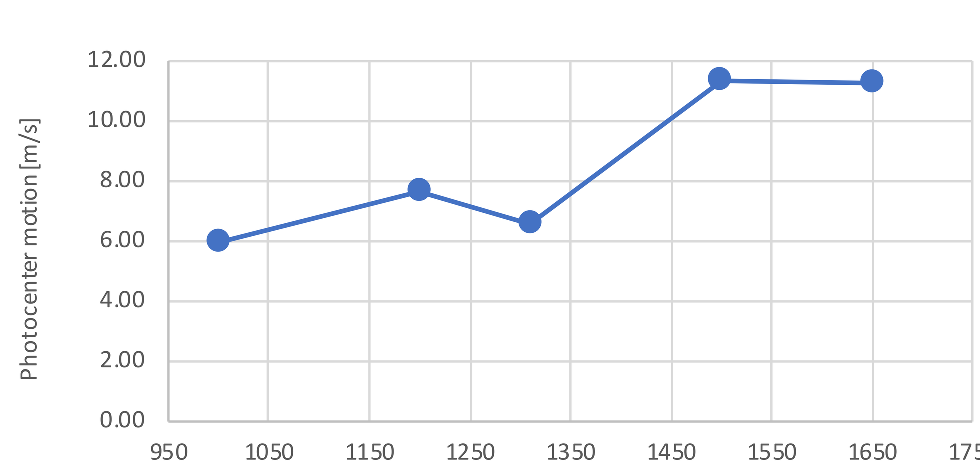


Fig. 3 – Photocenter instability in the near-field of the 0.4" fiber

DOUBLE SCRAMBLER

- Near-field and far-field are not independent anymore
- Few-mode fiber intrinsic scrambling efficiency is low

→ double scrambler not effective

- Near-field to far-field modes mismatch costs 10-20% in throughput
- Performance estimated by injecting far-field measurements into spectrograph optical design (Fig. 4)

> The double scrambler does not improve pupil stability in the few-mode regime

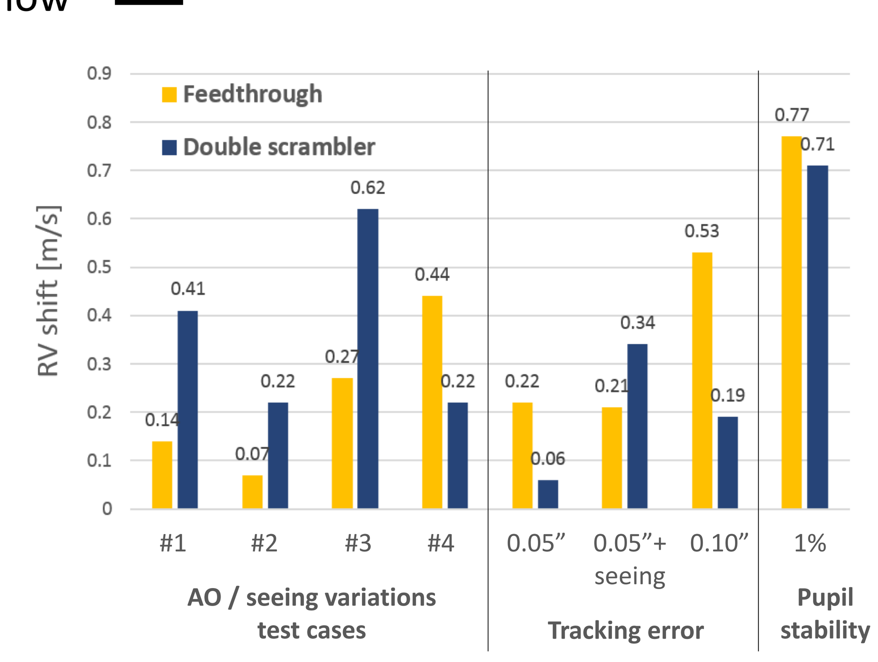


Fig. 4 – Standard feedthrough and double scrambler sensitivity to different sources of error

FIBER SCRAMBLING WITH DM

- DM is used to couple light to the various modes of the fiber
- Mode-selective coupling is possible to some extent, but is not photon efficient
- Zernike OPD masks allow smoother behavior

Blind+, 2017 (AO4ELT)

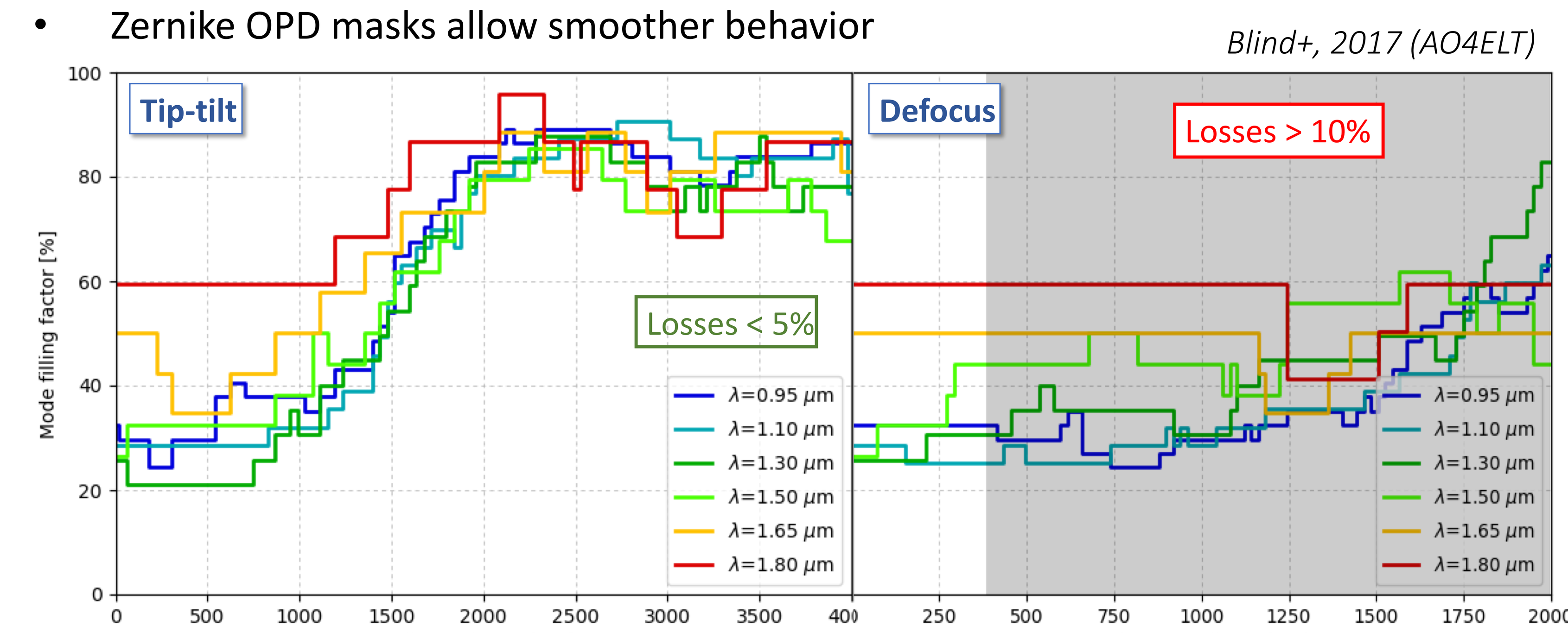


Fig. 5 – Fiber filling factor when applying a Zernike OPD on DM. Grey area shows 10% coupling loss from optimal.

> Tip-tilt scan is the most efficient term, with a scrambling gain of ~10

FIBER STRETCHER

- Fiber Stretcher modulates the phase between modes → uniformizes interference pattern (Fig. 8)
- 7mm stretch ⟺ ΔT=25K over 50m of fiber
- ➢ Makes illumination independent of external factors such as temperature, varying stress on fiber during tracking, etc.

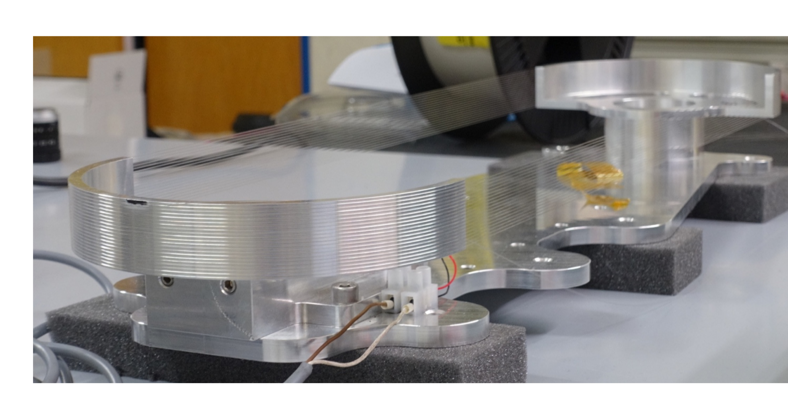


Fig. 6 - Prototype stretcher with 7mm total modulation amplitude @20Hz

Performance

- Throughput > 90%
- Scrambling gain ~ 4

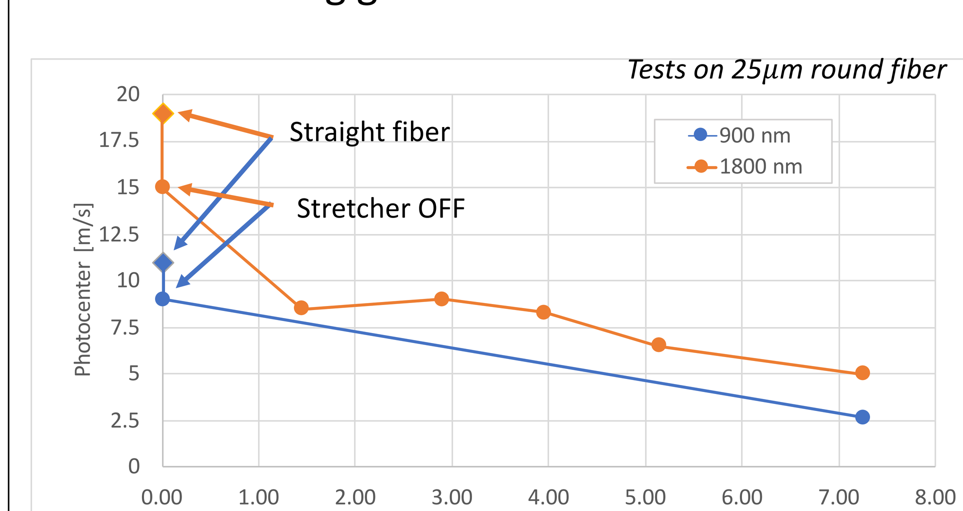


Fig. 7 – Modal noise in m/s VS stretch amplitude.

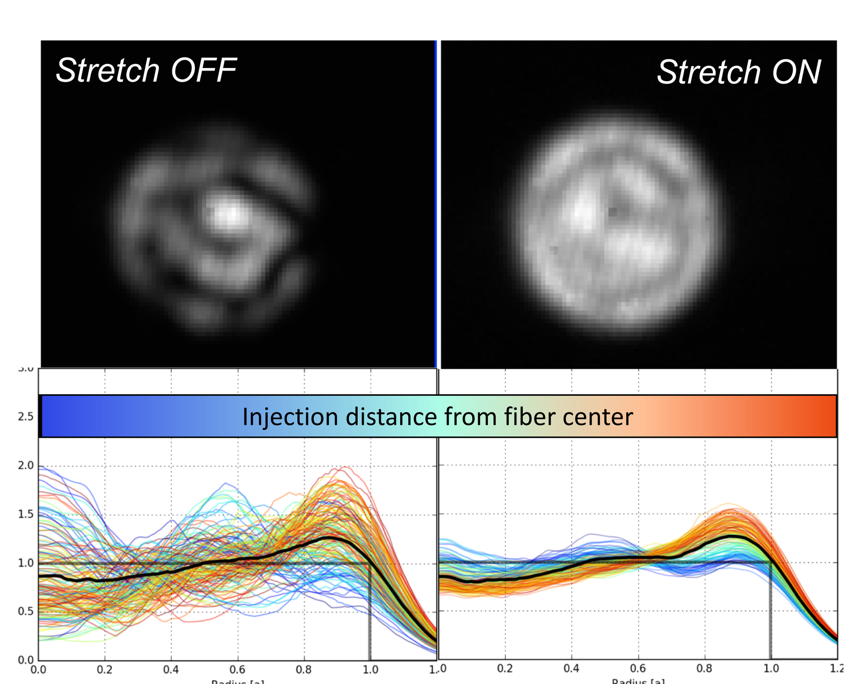


Fig. 8 – Near-field output image (top) and radial profiles vs injection position (bottom).

RADIAL VELOCITY BUDGET

	Scrambling gain	RV
Octagonal fiber 0.4" [980-1800nm]	300	< 10 m/s
Double scrambler	1	< 10 m/s
DM Tip-Tilt	10	< 1.0 m/s
Stretcher	4	< 25 cm/s
NIRPS total		**< 25 cm/s**