NIRPS modal noise mitigation and reduction techniques

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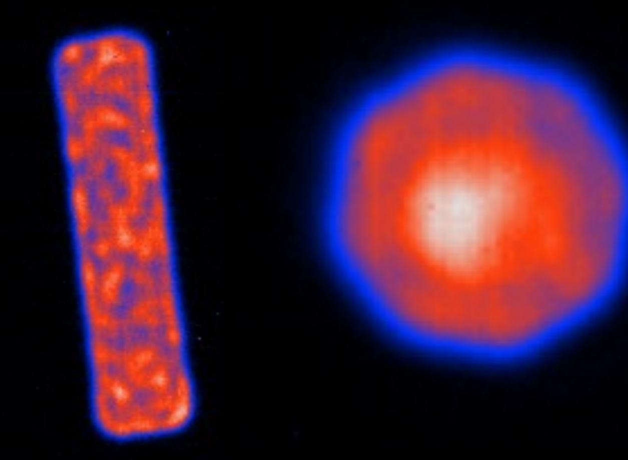
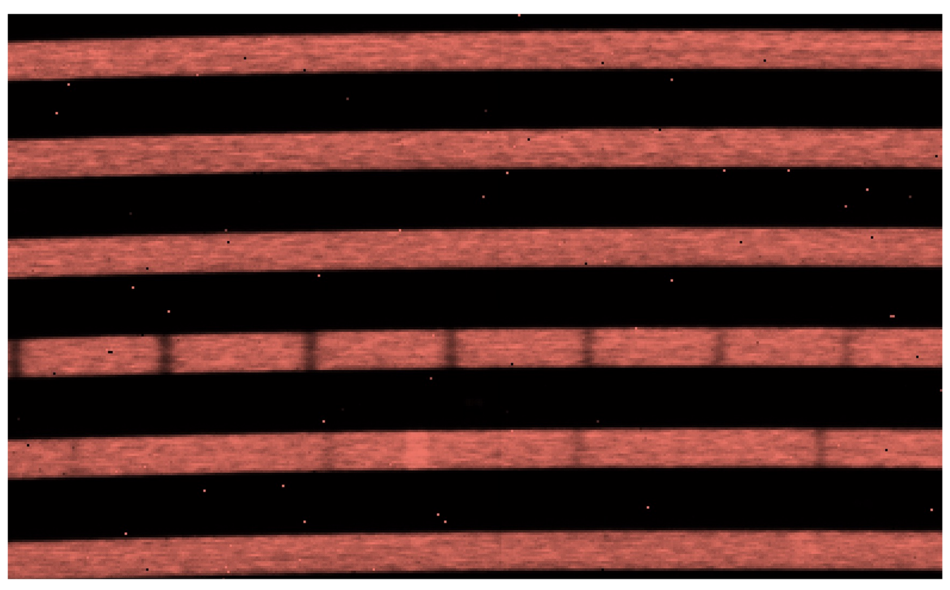
NIRPS (Near Infra-Red Planet Searcher) is a high-resolution spectrograph that operates in the YJH-bands at the ESO 3.6m telescope in La Silla Observatory, Chile. This instrument is assisted by adaptive optics (AO) and fed by four fibers that offer two observing modes: a high-accuracy mode (HA), which uses a 0.4″ FoV fiber, and a high-efficiency mode (HE), which employs a 0.9″ FoV fiber coupled to a pupil slicer. To couple the starlight into the relatively small (29-μm) multi-mode fiber and achieve a precision of 1 m/s in radial velocity, NIRPS uses a high-order AO system and combines several techniques, including octagonal fibers, a fiber stretcher, a double-scrambler, and tip-tilt scanning of the fiber core. These measures optimize geometrical scrambling and minimize modal noise.



Near-Field Images of the 33x132 μm rectangular HE fiber without stretcher (Left) and the 29-μm octagonal HA fiber with stretcher (Right) illuminated with a 1.55 μm laser and the diffraction limited PSF of the Front-End. Modal noise is clearly visible. Note: image scale is not the same.

Overview of the NIRPS fiber link with its different sub-components.

In June 2022, the first commisioning with the entire instrument took place and NIRPS had its first light. We investigated the modal noise properties by observing fast-rotating hot stars. Clear structures at the 2.5-6% level appear in the continuum of stellar spectra after flat-field correction, especially in the H-band.

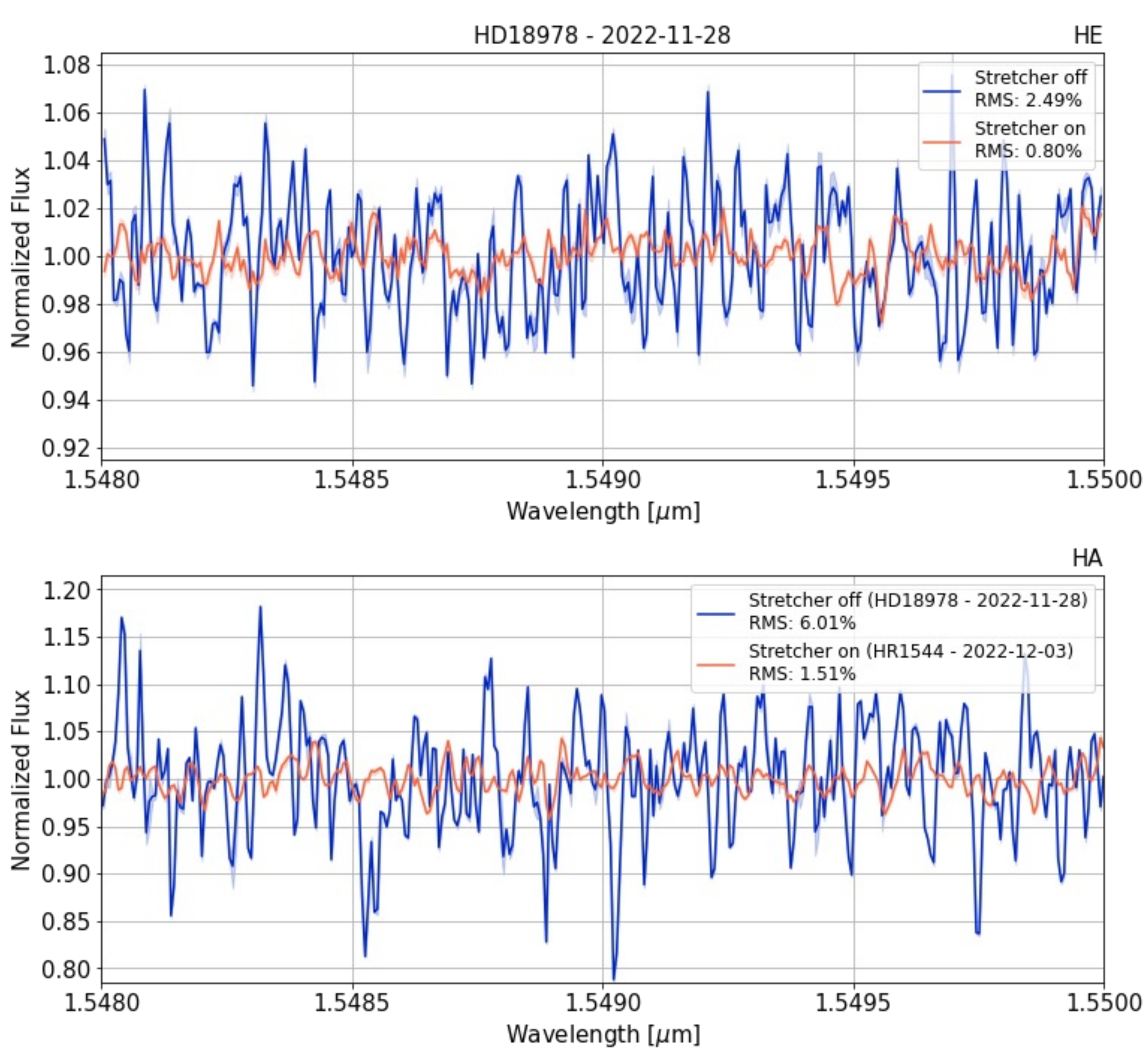


Zoom on a portion of the NIRPS raw frame in the H band of HD195094 observed in HE mode illustrating modal noise. The few spectral features correspond to telluric lines.

We investigated the amplitude of the modal noise by measuring the dispersion on the continuum of feature-less spectra. The modal noise structures are found stable for a few hours and to depend on the fiber injection. The stability is still under investigation.

On sky tests with and without stretcher

The HA fiber was equipped with a stretcher from the beginning. After observing a significant amount of modal noise in HE (as evident in the near-field images), a stretcher was also installed on the HE fiber. Upon comparing the modal noise measured in the HE spectrum with and without the stretcher, a significant reduction is observed, from 2.5% to 0.8%. Which is without the use of AO scrambling. A similar decrease is also seen in HA, again excluding AO scrambling, the modal noise reduces from 6% to 1.5%. The stretcher reduces the modal noise significantly.

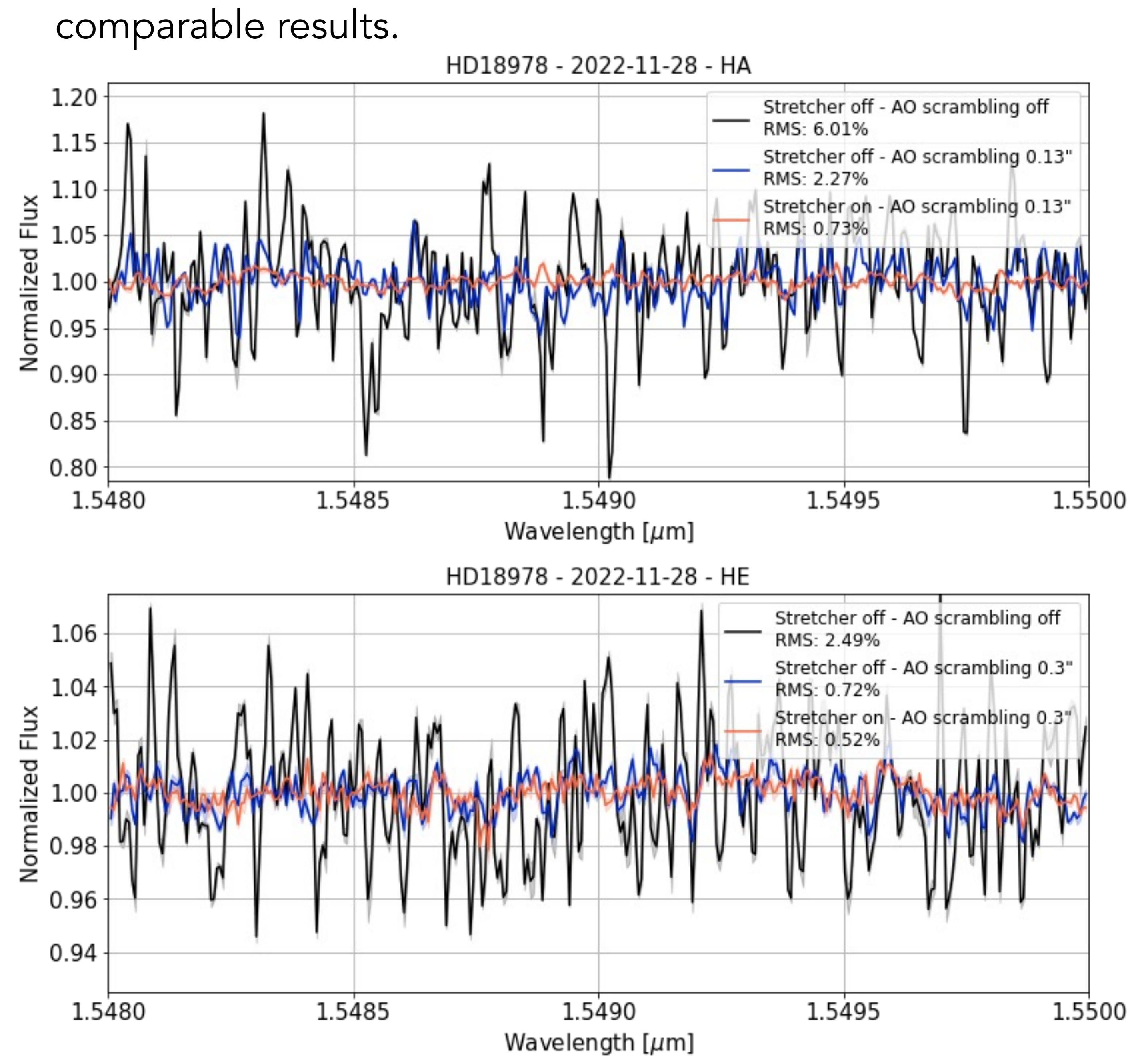


A portion of the spectrum extracted from the H-band (1.55 μm) observations of the fast-rotating stars HR18978 and HR1544, obtained in HE (up) and HA (down).

All spectra were taken without AO scrambling. The photon noise contribution is at 0.3%.

On sky tests with and without AO tip-tilt scanning

The effectiveness of AO scrambling (performed via tip-tilt scanning) was tested by varying the region where light is injected into the fiber. When no AO scrambling is applied and only a partially corrected image is injected at the center of the fiber core, the HA fiber (0.4″) exhibits modal noise of about 6%. Tip-tilt scanning of the fiber entrance reduces modal noise, with a circular region up to ~0.1″ found to be most effective. This approach significantly reduces the modal noise amplitude from 6% to 2.3%. Which is then further reduced when including the fiber stretcher to 0.7%. Avoiding central modes does not result in further improvement of the observed signal. For the HE fiber the effectiveness of AO scrambling was also tested. Tip-tilt scanning was found to reduce the modal noise from 2.5% to 0.7%. Which is again further reduced with the fiber stretcher to 0.5%. Avoiding central modes yields comparable results.



A portion of the spectrum extracted from the H-band (1.55 μm) observations of the fast-rotating star HR18978, obtained in HA (up) and HE (down).

The photon noise contribution is at 0.3%.

The observed noise is more dominant towards the red and is dependent on how the light is injected into the fiber. The HE fiber exhibits less noise than the HA fiber, which is consistent with modal noise. Modal noise increases with longer wavelengths and depends on the number of modes filled. The HE fiber is larger and can accommodate more modes, leading to better scrambling of the light and resulting in lower modal noise. However, it is possible that other factors may contribute to the noise. The observed noise creates a limit for the achievable signal-to-noise ratio. For example, a noise level of 0.5% corresponds to an SNR of 200.

Fiber modal noise can severely limit NIR spectroscopy. However, both the NIRPS fiber stretcher and the NIRPS AO tip-tilt scanning have shown their effectiveness in significantly reducing modal noise on-sky. The AO scanning pattern is optimized to minimize modal noise, while residual quasi-static modal noise can also be calibrated on fast-rotating hot stars, as the structures seem relatively stable for a few hours.

References:
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