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High-resolution integral-field spectroscopy of exoplanets

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3 | On-sky results of the Leiden EXo-planet Instrument(LEXI)

Adapted from

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The Leiden EXoplanet Instrument (LEXI) is a bench-mounted high-contrast spectrograph (HCS) and high-contrast imager(HCI). Both science instruments are mounted behind a common adaptive optics (AO) system. The AO can be controlled by several new wavefront sensors for which we will show the first on-sky results. There is a new pupil-plane wavefront sensors; the Generalized Optical Differentiation Wavefront sensor(g-ODWFS). LEXI can switch between two observing modes, the HCI mode or the HD-IFS mode.

The spectrograph is very compact because it is fed by single-mode fiber. The HD-IFS is an IFS that covers the spectral range of 600 – 800 nm with a constant spectral resolving power of 96000. The 2kx3k detector makes it possible to deliver diffraction limited spectra of up to 20 input fibers. The high-dispersion spectra of the HD-IFS allow for robust post-processing technique to remove residual stellar speckles and allows for direct characterization of the faint stellar environment. We will show the first succesful on-sky results of the injection into a single-mode fiber with LEXI.

In HCI mode an Apodizing Phase Plate (APP) is used to create a dark region around the star with an average design contrast of 1E-4. The APP is multiplexed with holographic modes to create the Coronagraphic Modal Wavefront sensor (cMWS) for non-common path error (NCPE) correction. The cMWS creates holographic copies in the focal plane that react linearly to aberrations. The holographic copies are measured simultaneously with the science target. There is no downtime for NCPE correction. We will show the first on-sky closed-loop correction of (NCPEs) with the cMWS.

3.1 Introduction

The discovery of Proxima Centauri b (Anglada-Escudé et al., 2016) shows that the solar neighbourhood has many planets waiting to be discovered. Current surveys show that most habitable zone planets have a separation near the diffraction limit of current and future large telescopes. Many exoplanets are found through indirect methods such as radial velocity or transit measurements. Both are very successful at finding exoplanets. But the only way to unambiguously characterize the atmospheres of exoplanets is through direct imaging where the photons of the planet are separated from the photons of the star. This is achieved through high-contrast imaging(HCI) where advanced optical techniques are applied to suppress the stellar light at the position of the planet.

For ground-based telescopes the major limitation for exoplanet characterization is the Earth's atmosphere. The atmosphere causes wavefront errors due to turbulence and temperature fluctuations. These wavefront errors limit the spatial-resolution of the telescope. High-speed adaptive optics(AO) is necessary to correct for the wavefront errors. With AO the telescope can reach its diffraction limit again. However not all wavefront errors are corrected. There are residual wavefront errors, which are due to errors in the measurements of the wavefront or due to certain modes that the AO cannot correct. To control the AO system the wavefront errors need to be sensed which is done by a wavefront sensor.

Another limitation is set by the difference in optical path of the science instrument and the AO wavefront sensor. Because there are optics which are not in the common path of both systems there will be wavefront errors that are not sensed by the AO system. These are called NCPAs and are usually of a low-order. These low-order NCPAs are the main limitation for deep starlight suppression by the coronagraph close to the star. Currently there is a lot of research focused on the active control of the NCPAs by using focal-plane wavefront sensing (FPWFS) (Jovanovic et al., 2018).

After AO and NCPA correction it is still possible to have residual speckles in the focal plane. Smart post-processing methods are necessary to discern whether the speckle is a planet or light from the star. Most conventional post-processing methods use spatial diversity to remove the residual speckles of the star. But this leads to problems at small inner working angles where the speckles change by large amounts due to slowly changing NCPAs. A very promising approach that has recently been explored is the combination of high-resolution spectroscopy together with high-contrast

imaging (Snellen et al., 2015). High-contrast imaging spatially separates the planet from the star and overcomes part of the large contrast between the objects. High-resolution spectroscopy(HRS) can be used to gain additional orders of magnitude and suppress the star enough to characterize the exoplanets atmosphere. At high-resolution the spectral lines from the planet and star can be separated. The difference in spectral lines is due to a difference in radial velocity and/or a difference in molecular composition. Using matched spectral filters it becomes possible to remove the residual starlight and discover and characterize exoplanets at the same time.

The Leiden Exoplanet Instrument(LEXI) is a HCI pathfinder instrument that is being developed at Leiden. LEXI is a bench-mounted visiting instrument for the William Herschel Telescope(WHT) at La Palma. LEXI consists of an AO system that feeds two different instruments, a high-contrast imager and a high-contrast spectrograph(HCS). The main purpose of LEXI is to explore the power of HCS for exoplanet detection and characterization. It is the first instrument that is specifically designed for HCS in the visible band. As LEXI is a pathfinder instrument it uses several newly developed techniques for HCI. An overview of the modules of LEXI will be given in section 2. Section 3 will show the improvement of the AO system and the first on-sky results of the newly developed generalised-Optical Differentiation wavefront sensor (Haffert, 2016). In section 4 we will discuss the sensing, calibration and control of NCPAs with the coronagraphic Modal Wavefront Sensor(cMWS) (Wilby & Keller, 2016; Wilby et al., 2017). And section 5 will show the results of the HCS.

3.2 LEXI overview

We observed with LEXI in December 2017 during the observing run LEXI consisted of three modules. A sketch of the system is shown in Figure 3.1. This was the second observing run of LEXI at the WHT (Haffert et al., 2016). During that run we experienced that our AO system was not of high enough order to correct for the full aperture. There were two options for this run either the DM was replaced with a higher order DM or we stop down the aperture. We decided to stop down the aperture as this was an option that was cheaper and was quicker to implement compared to the lead time of a new DM. The geometry of the stopped-down aperture is show in Figure 3.2. The diameter of the off-axis segment was based on the actuator count of our Alpao 97-15 DM. The Alpao 97-15 DM has 11 actuators across the pupil. Because the Alpao DM has actuators on the

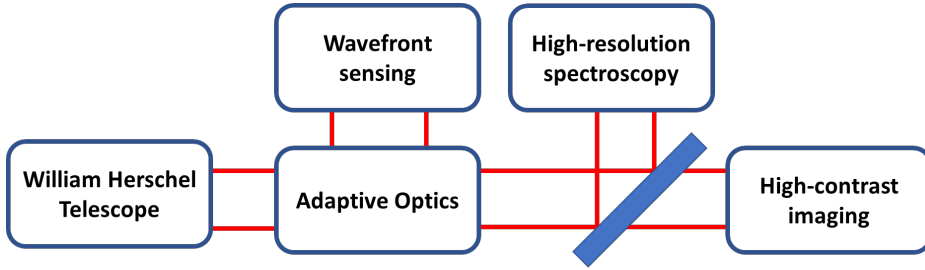


Figure 3.1: This is a sketch of the LEXI modules. The light from the WHT is fed into an AO system which feeds two different backends. The science instruments are an high-contrast imager and a high-contrast spectrograph.

edges of the mirror the effective degree of freedom is $N - 1$. To correct for most turbulence we have to match 1 degree of freedom to 1 patch of turbulence. At the WHT there is a median seeing of 1 arcsecond, which corresponds to a r_0 of 10 cm at 550 nm. LEXI has a spectral range from 0.6 μm to 0.9 μm . To match the median seeing over the whole wavelength range we decided on an off-axis segment of 1.2 meter.

We do not have a derotator in our system and this causes the spiders to come in and out during observations. With a few small simulations we estimated that the effects of the spiders were negligible compared to the residual wavefront errors of the atmosphere. Therefore we decided against implementing a derotator.

LEXI is bench-mounted on an optical table at the Nasmyth focus of the WHT. The light from the Nasmyth focus of the WHT passes through a small optical relay which consisted of two achromatic doublets with a focal length of 100 mm and 25 mm respectively. In the intermediate pupil plane we placed an aperture stop. This relay was designed with the idea to accommodate a potential atmospheric dispersion compensator for a future version of LEXI. After the relay the light is collimated by a 140 mm achromatic doublet. The projected pupil size of the off-axis segment is 13.5 mm which fully illuminates the DM. The DM can run at frequencies up to 900 Hz and has a stroke of 60 μm . This allows for corrections of large aberrations. The beam is redirected by a second fold mirror after the DM. The beam is then focused by an identical lens as was used for the collimation. This creates a 1-to-1 system between the AO input and output.

The focused beam passes through a 50-50 cube beam splitter. Half of the light is sent towards the wavefront sensor arm and the other half is sent

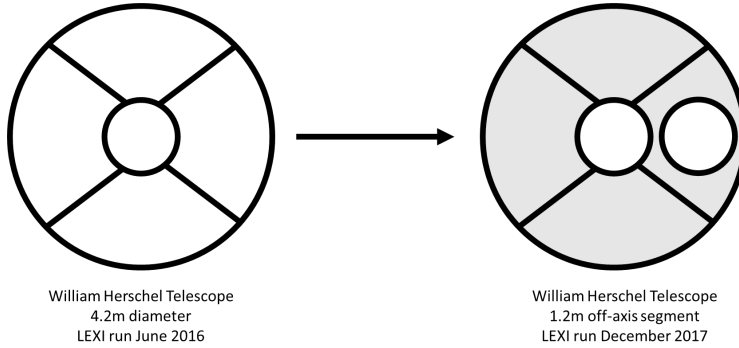


Figure 3.2: This is a sketch of the LEXI modules. The light from the WHT is fed into an AO system which feeds two different backends. The science instruments are an high-contrast imager and a high-contrast spectrograph.

towards the science instruments. Both the wavefront sensor and the science instruments use the same wavelength range and share the photons. For the science beam the light collimated by a 50 mm achromatic doublet. This creates a 4.7mm pupil of which a 4.55mm pupil is cut-out by a liquid-crystal plate. The liquid-crystal plate contains our pupil plane coronagraphs and acts as a pupil stop at the same time. The pupil stop is created by using a very high frequency grating creating a grating mask (Doelman et al., 2017). The imaging is done with a last 2 inch 300 mm lens. This creates a PSF that is sampled with about 3 pixels per λ/D at 700nm.

3.3 The adaptive optics module of LEXI

The wavefront sensor of LEXI has been changed from a Shack-Hartmann wavefront sensor to a generalized Optical Differentiation Wavefront Sensor (g-ODWFS). This is a new wavefront sensor which was recently developed in Leiden (Haffert, 2016). The g-ODWFS uses focal plane amplitude masks to filter the incoming light to sense the wavefront in the pupil plane. A sketch of the g-ODWFS principle is shown in Figure 3.3. The g-ODWFS has several advantages over the SHWFS. The foremost advantages is it's sensitivity which is close to a modulated pyramid wavefront sensor. A second advantage is that the wavefront sensor manipulates the light in the focal plane allowing for arbitrary sampling in the pupil. Because the sampling only depends on the camera we can be adjust the sampling on the fly

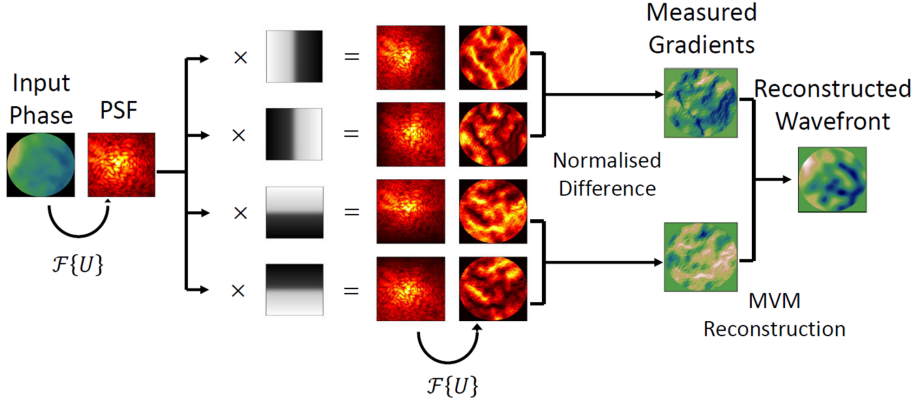


Figure 3.3: This figure is adapted from Haffert 2016 (Haffert, 2016). The input pupil is focused by a lens and filtered by 4 focal plane masks. Each filtered PSF is collimated which results in 4 pupils. The normalized difference of the pupils encodes the wavefront slope. The wavefront is reconstructed with a matrix-vector multiplication.

by binning the camera. We made use of this by oversizing the pupils on purpose and then used the highest binning setting with which we could still operate all DM modes. The camera of the wavefront sensor is an Andor iXon EMCCD with 128x128 pixels which can run at 512 Hz while reading out the full frame. Because we binned the camera we could increase our AO loop speed to 800 Hz, which was limited before by the frame rate of the camera. The pupils were sampled with 16 pixels across which is still oversampled with respect to the actuators.

Normal amplitude filters are not photon efficient, they will always throw away light. Therefore the amplitude filters of LEXI were implemented with patterned liquid-crystals(LC). The LC act as a spatially varying half-wave plate. This plate will rotate linear polarized light by an amount which is determined by the position on the focal plane mask. After the focal plane mask the light is split into two pupils with a Wollaston prism. The angle of the polarization after the LC plate determines the relative transmission between the two outgoing pupils. So we can implement amplitude filters by acting on the angle of polarization. Because the LC plate needs linear polarized light we place a polarization beam-splitter cube up-stream of the LC plate. This has a nice advantage as we can use the two output

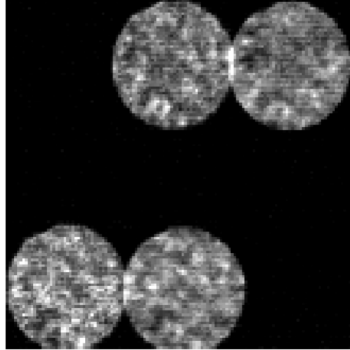


Figure 3.4: The output of the g-ODWFS during on-sky operation. The left and right pair of pupils are modulated with an opposite intensity pattern. This asymmetry is caused by wavefront aberrations. There is still a detector artifact left in the pupil images which is due to a non-perfect estimated bias.

polarizations of the beam-splitter cube for sensing the wavefront gradient in two directions. The final output pupil configuration is shown in Figure 3.4.

The combination of an off-axis segment and the new wavefront sensor led to a great improvement in quality of PSF. The first on-sky results of the g-ODWFS can be seen in Figure 3.5. The wavefront sensor closed the loop on-sky for the first time without any issues. The Full-Width at Half-Maximum(FWHM) changed from $4.3 \lambda/D$ in natural seeing to a diffraction-limited FWHM of $1 \lambda/D$. The seeing during the observation is estimated at $0.64''$ from the FWHM of the seeing-limited PSF. The quality of the AO correction allowed us to use a coronagraph to increase the raw contrast. This can be seen in Figure 3.5 where the AO-corrected PSF is a one-sided vector Apodizing Phase Plate(vAPP) (Otten et al., 2014; Snik et al., 2012) coronagraphic PSF. With the vAPP and the improved AO we were able to reach 5σ contrast of $1E-3$ at from $2\lambda/D$ and further. This can be seen in Figure 3.6. The contrast gain is factor of 10 to 200 depending on the distance from the star. This curve was measured from an imaging cube consisted of 250 frames with an individual exposure time of 0.07s. The cube was checked for temporal correlations between individual frames, but no correlation was found. Therefore we determined the 5σ contrast limits by taking the standard deviation of imaging cube in time and divided by the square root of the number of frames. Afterwards the normalization was

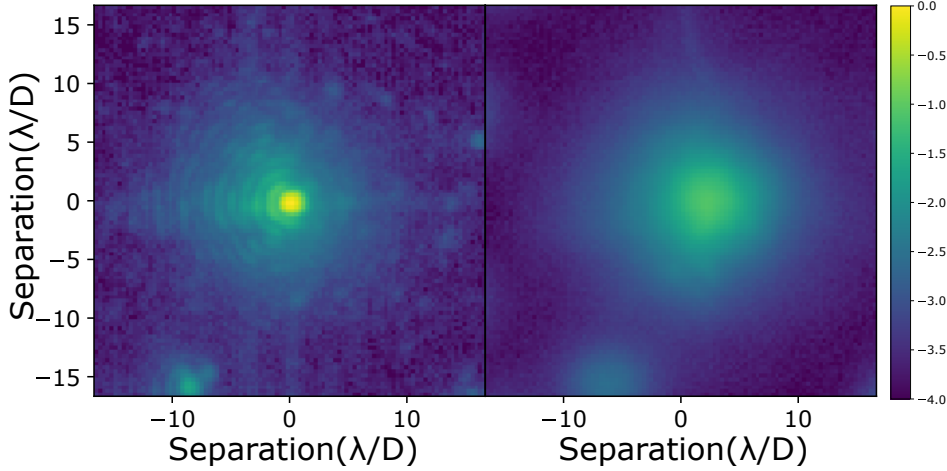


Figure 3.5: The figure on the left shows the closed-loop AO PSF and figure on the right shows the seeing-limited PSF. The AO improves the quality of the PSF substantially. The AO PSF is close to diffraction limit with a FWHM of $1 \lambda/D$.

done by the maximum of the mean-combined image. The results of this observation is encouraging as this contrast is reached with a total exposure time of only 17.5 seconds.

3.4 Focal-plane wavefront sensing with the cMWS

The contrast at small inner-working angles is mainly limited by low-order non-common path errors. The HCI arm of LEXI uses focal plane wavefront sensing to sense and actively correct for NCPAs. The focal-plane wavefront sensor is a coronagraphic Modal Wavefront sensor. The cMWS is a holographic wavefront sensor that can be multiplexed together with a vAPP. The hologram generates spatially separated secondary PSF copies in the science focal plane. For each wavefront aberration two oppositely biased satellite spots are generated. The difference between the Strehl ratio of the two copies reacts linearly to the amplitude of the selected wavefront aberrations. This makes the cMWS a fast and real-time wavefront sensor for focal-plane wavefront sensing.

The design for LEXI is shown in Figure 3.7. The cMWS is multiplexed with a 360 degree dark hole vAPP. The dark hole contrast is $1\text{E-}4$ from 3 to

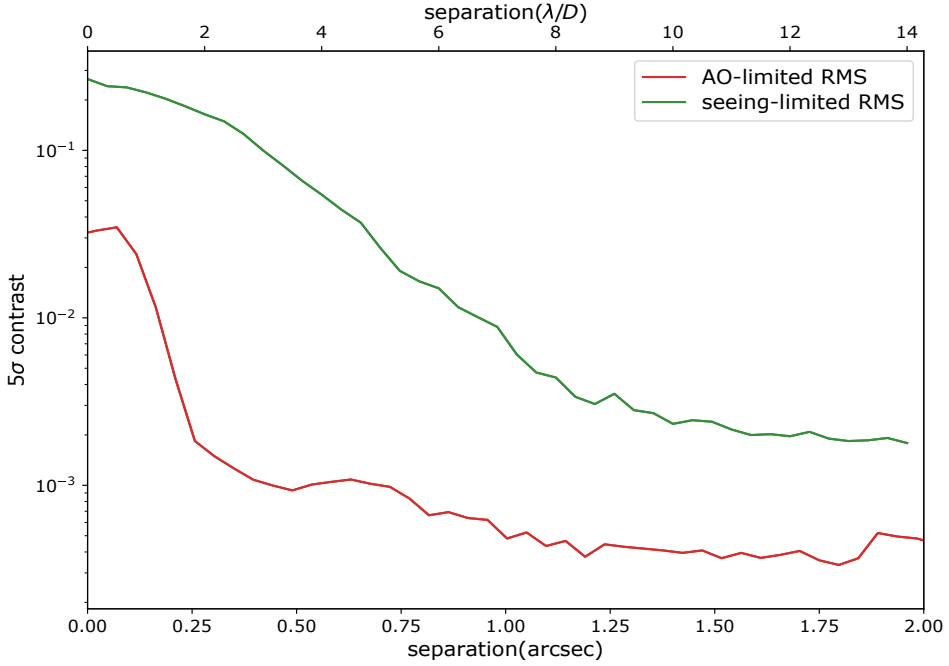


Figure 3.6: The post-processed 5σ contrast curves of LEXI. These curves were generated from a 17.5 second data cube. The contrast is $1\text{E-}3$ from $2 \lambda/D$ and further. The gain in contrast compared to the seeing-limited PSF is significant. This gain varies from a factor of 10 to 200 depending on the angular separation.

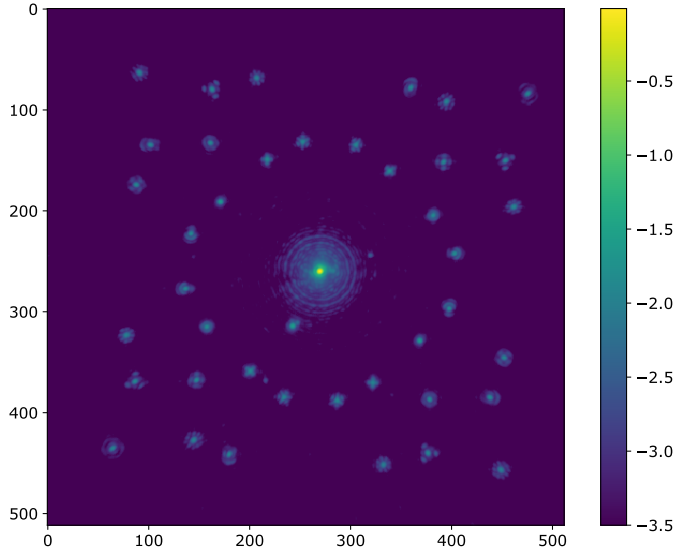


Figure 3.7: The multiplexed focal plane of the cMWS. The cMWS is multiplexed with a 360 degree dark hole vAPP. The vAPP creates a $1\text{E-}4$ dark hole from 3 to $6 \lambda/D$. The cMWS is multiplexed with 20 Disk Harmonic modes.

$6 \lambda/D$. The vAPP is multiplexed together with 20 Disk Harmonic modes. The Disk Harmonics(DH) were chosen over the Zernike modes as the edge behaviour of the DHs is more regular. There is also a ghost visible on the bottom left of the stellar PSF. The cMWS was calibrated by applying the DH modes iteratively on the DM. From the response of the cMWS to the DM modes we build up an interaction matrix. This takes care of any linear cross-talk between the sensed modes and calculates the gain between the sensor and the DM. The calibration was done with the internal light source during the day. Any NCPA sensed by the cMWS was sent to the high-speed g-ODWFS as a reference offset for the slopes.

The closed-loop feedback was successfully tested on Regulus. This can be seen in Figure 3.8. The quality of the PSF increases after the loop on the cMWS has been closed. The first Airy ring became more circular. The outer edges of the diffraction structure were also closed to the designed

structure. The improvement in contrast can be seen in 3.9. The contrast improves by a factor of 1.5-2. This is more evident by looking at the sensed wavefront rms in Figure 3.10. After the loop closes the wavefront rms decreases by a factor of 1.5-2.

3.5 Single-mode fiber-fed spectroscopy

High-contrast spectroscopy is a robust technique for removing speckle noise. It has been used to characterize the atmosphere of giant exoplanets and determine the spin rate of these planets. LEXI will have an fiber-fed IFU spectrograph in the future. The current baseline design is to use a single-mode multi-core fiber for the IFU. But is it notoriously difficult to couple efficiently into a single-mode fiber (Bechter et al., 2016; Jovanovic et al., 2014; Jovanovic et al., 2017). An important experiment is to see whether LEXI is able to inject light into a single-mode fiber-fed spectrograph. The spectrograph of LEXI has been designed to reach a spectral resolving power of 100000 from 600 to 900 nm for 19 fibers. The spectrograph itself is a cross-dispersed echelle spectrograph. Because the input is diffraction-limited due to the single-mode fiber the spectrograph itself is very small in size. A photo of the assembled spectrograph can be seen in Figure 3.11.

To keep the design relatively simple we opted to go for a special kind of single-mode fiber, a photonic crystal fiber(PCF). The PCF we used was a Large Mode Area fiber (LMA). LMA fibers are fibers with a large Mode Field Diameter which can be up many tens of microns. We used the LMA-15 of NKT-photonics which had a MFD of 12.5 μ m. This is ideally suited to the SBIG STF-8300 CCD camera which has a pixel size of 5.4 μ m. Due to the matching of the sizes no reimaging optics are necessary to change the F-ratio of the beam. To reach the large MFD the NA of the fiber has to be low, and is around 0.05 for our wavelength range. This makes it relatively easy to collimate the beam. For the collimator we decided to use an off the shelf Thorlabs tube lens, the TTL200MP. This infinity-corrected tube lens is an apochromatic design with a diffraction-limited field of view of ± 11 mm designed to operate from 400 nm to 2000 nm. After the collimation the beam will be pre-dispersed by a 18 degree BK7 wedge prism of Thorlabs and then dispersed by an Thorlabs R2 echelle grating with 31.6 lines/mm. After the reflection of the echelle grating the beam will through the wedge prism a second time. The collimating tube lens is also used as a camera lens. Because of it's wide field of view and broad wavelength performance, the lens is able to deliver a diffraction-limited cross-dispersed spectrum on

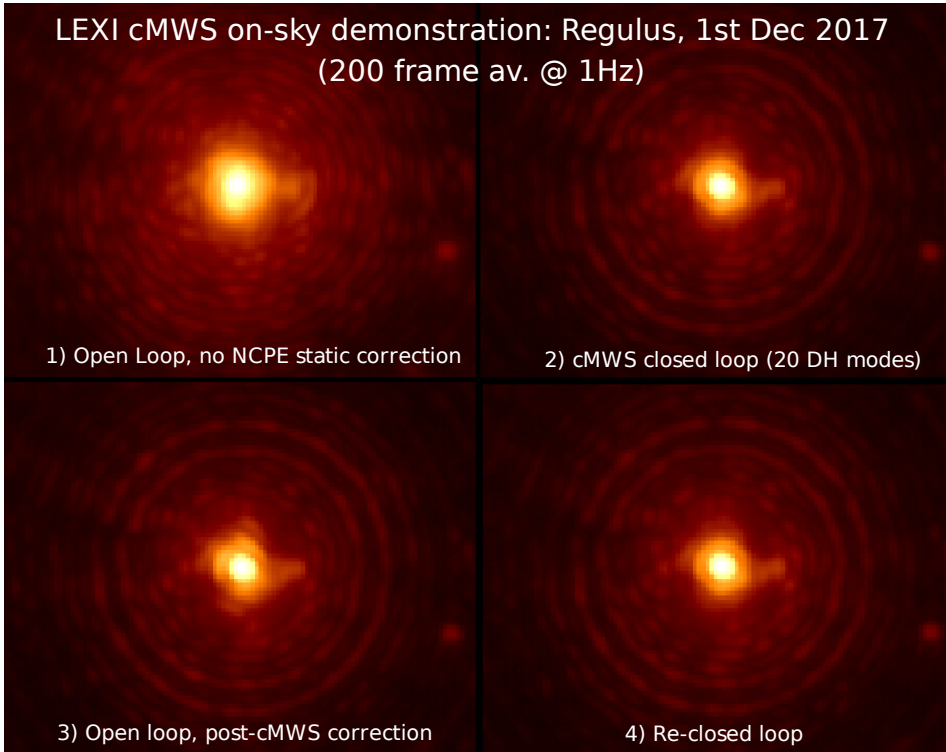


Figure 3.8: A sequence of stacked images of the PSF during operation of the cMWS. During closed-loop feedback of the cMWS the PSF clearly improves in quality. The asymmetric feature in the first panel has been fixed and the first Airy ring looks nice and round. After the first round of feed-back the loop is opened again and the NCPA's are allowed to evolve again. The last panel shows the closed loop PSF after that.

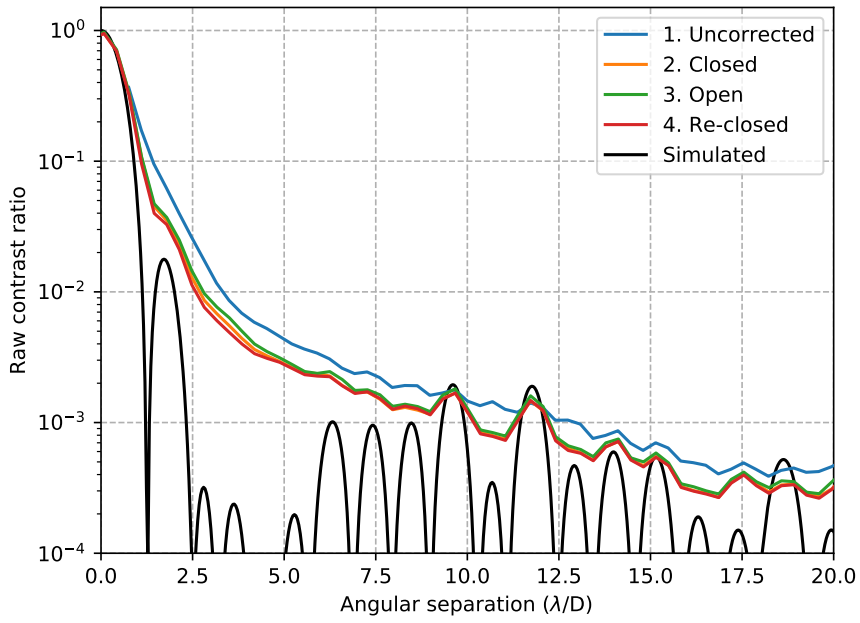


Figure 3.9: The contrast curve of Regulus with the 360 vAPP dark hole. The cMWS does improve the raw contrast by a factor of 1.5-2. We do not however reach the design contrast.

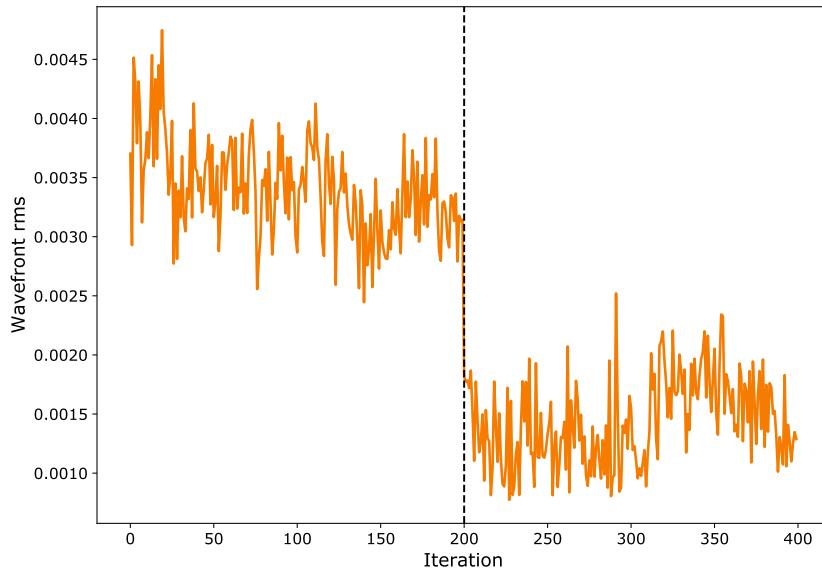


Figure 3.10: The wavefront rms as measured by the cMWS. The wavefront rms gain is not calibrated therefore only the relative change is important. The black dashed line indicates the moment that the cMWS starts to give feedback. The wavefront rms as measured by the cMWS decreases by a factor of 1.5-2 which is exactly the gain in contrast that was achieved.

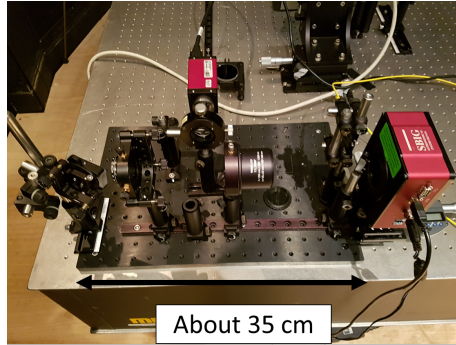


Figure 3.11: A picture of the single-mode fiber-fed spectrograph of LEXI. The spectrograph footprint is about 35 cm by 25 cm. It is a minimal design with 1 fold mirror, 1 collimator/camera lens 1 prism and 1 grating. The spectrograph is fed by a LMA-15 fiber from NKT photonics which is dispersed on a SBIG STF-8300 camera. A fold mirror can be entered to look at the broadband output of the fiber without dispersion.

the detector.

An advantage of the LMA fibers is their constant MFD as function of wavelength. To keep this property the F number changes as the wavelength changes. This exactly cancels out the wavelength dependence of the spectral resolving power of a grating. Therefore the spectral resolving power is almost constant across the whole wavelength range. An example of the spectra that were obtained with the LEXI spectrograph can be seen in Figure 3.12. The oxygen absorption lines from the Earth's atmosphere are very clear in the spectrum. These oxygen lines have also been used to estimate the spectral resolving power of the spectrograph, which was calculated to be 92000 which was very close to the designed resolving power of 96000.

3.6 Conclusion and outlook

The strategy to change the wavefront sensor and stop down the aperture was very successful. The first on-sky results of the g-ODWFS are very encouraging and showed that it worked under natural seeing conditions and with broadband light. The improved Strehl and PSF quality allowed us to apply high-contrast imaging techniques. This led to the successful closed-loop demonstration of the cMWS. The cMWS has shown to increase

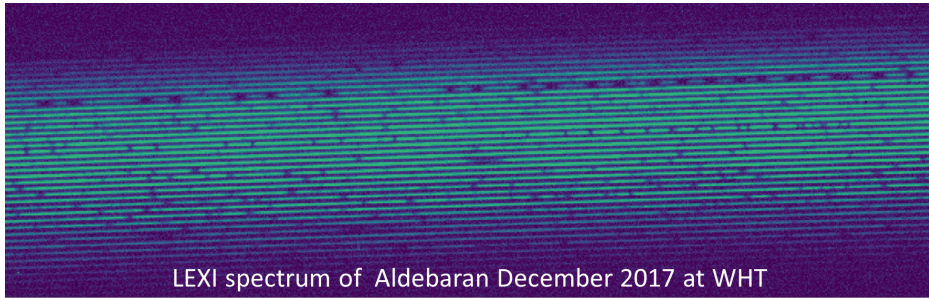


Figure 3.12: This is a cross-dispersed spectrum of Aldebaran. The integration time of this spectrum is 40 minutes with a SNR of 30-40 on the continuum. The spectrum shows very clear and deep spectral lines, which indicate the high-quality and high-resolution of the spectrum.

the contrast by a factor 1.5-2 which is also indicated by the sensor itself as the wavefront rms has also decreased by a factor of 1.5-2. LEXI was also able to inject light efficiently into a single-mode fiber-fed spectrograph. With Aldebaran we measured the design parameters of the spectrograph and confirmed that it reached the requirements.

LEXI is currently being upgraded with a major component being the upgrade of the spectrograph. It will change from a single single-mode fiber-fed spectrograph to a multi-core fiber-fed spectrograph. It will allow up to 20 fibers at a spectral resolving power of 100000 between 600-900nm. An important aspect during this upgrade is the addition of an ADC. The ADC becomes necessary as we want to couple the high-resolution spectrograph with more advanced coronagraphic techniques which need well corrected tip/tilt otherwise there will be stellar light leaking through.

Bibliography

- Anglada-Escudé, G., Amado, P. J., Barnes, J., et al. 2016, *Nature*, 536, 437
- Bechter, A., Crass, J., Ketterer, R., et al. 2016, in *Proc. SPIE*, Vol. 9909, *Adaptive Optics Systems V*, 99092X
- Doelman, D. S., Snik, F., Warriner, N. Z., & Escuti, M. J. 2017, in *Proc. SPIE*, Vol. 10400, *Techniques and Instrumentation for Detection of Exoplanets VIII*, 10400 – 10400 – 12
- Haffert, S., Wilby, M., Keller, C., & Snellen, I. 2016, in *Ground-based and Airborne*

- Instrumentation for Astronomy VI, Vol. 9908, International Society for Optics and Photonics, 990867
- Haffert, S. Y. 2016, Optics Express, 24, 18986
- Jovanovic, N., Guyon, O., Martinache, F., Schwab, C., & Cvetojevic, N. 2014, in Proc. SPIE, 91477P–91477P
- Jovanovic, N., Schwab, C., Guyon, O., et al. 2017, A&A, 604, A122
- Jovanovic, N., et al. 2018, in Proc. SPIE, Vol. 10703, Adaptive Optics Systems VI
- Otten, G. P. P. L., Snik, F., Kenworthy, M. A., Miskiewicz, M. N., & Escuti, M. J. 2014, Optics Express, 22, 30287
- Snellen, I., de Kok, R., Birkby, J. L., et al. 2015, A&A, 576, A59
- Snik, F., Otten, G., Kenworthy, M., et al. 2012, in
- Wilby, M. J., & Keller, C. U. 2016, in Proc. SPIE, Vol. 9909, Adaptive Optics Systems V
- Wilby, M. J., Keller, C. U., Snik, F., Korkiakoski, V., & Pietrow, A. G. M. 2017, A&A, 597, A112

