# High-resolution integral-field spectroscopy of exoplanets

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# 2 The Leiden Exoplanet Instrument (LEXI): a high-contrast high-dispersion spectrograph

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The Leiden EXoplanet Instrument (LEXI) will be the first instrument designed for high-contrast, high-dispersion integral field spectroscopy at optical wavelengths. High-contrast imaging (HCI) and high-dispersion spectroscopy (HDS) techniques are used to reach contrasts of $10^{-7}$. LEXI will be a bench-mounted, high dispersion integral field spectrograph that will record spectra in a small area around the star with high spatial resolution and high dynamic range. A prototype is being setup to test the combination of HCI+HDS and its first light is expected in 2016.

## 2.1 Introduction

One of the major drivers for current astronomical instrumentation development is the direct detection and characterization of Earth-like exoplanets. These developments are largely focused on improving high-contrast imaging techniques. But with the recent improvements of Extreme Adaptive Optics (AO) and coronagraphy (Jovanovic et al., 2015; Macintosh et al., 2014; Vigan et al., 2016), it is now possible to directly detect hot, self-luminous exoplanets. The current generation of high-contrast imaging instruments deliver a contrast between $10^4$ and $10^6$ after careful data reduction. The fundamental limit of raw contrast on ground-based telescopes is set by the AO system (Guyon, 2005). For 8-meter class telescopes this is roughly $10^6$. Earth-like exoplanets have a contrast on the order of $10^{10}$, which makes it necessary to have techniques that can bridge the gap between the AO contrast limits and the contrast of Earth-like planets.

Another technique to characterize exoplanets was developed at the same time as the HCI techniques. This technique makes use of the fact that the light of the planet is Doppler-shifted with respect to the star light. With a high-resolution spectrograph the stellar light can then be removed to extract the planet light. This method has already been successfully used to characterize several exoplanets (Brogi et al., 2012; Snellen et al., 2010). This high-dispersion spectroscopy technique has reached contrast limits of $10^5$.

Recently Snellen et al. (Snellen et al., 2015) proposed to combine high-contrast imaging with high-resolution spectroscopy. High-contrast imaging reduces the contrast between a star and its circumstellar environment; and high-resolution spectroscopy can then be used to remove the residual starlight. If we could reach $10^5$ with HCI and $10^5$ with HDS, then the combined contrast could reach $10^{10}$. The assumption here is that the two methods directly add their powers. The Leiden EXoplanet Instrument(LEXI) is the first instrument that will combine high-resolution spectroscopy with high-contrast imaging techniques in the visible. The main purpose will be to test the combination of HCI+HDS and see if we can directly add the achieved contrast limits of the individual techniques. LEXI is a visiting instrument for the 4.2m William Herschel Telescope (WHT) on La Palma.

The current version of LEXI is a prototype. This LEXI prototype will be operated in two observing modes simultaneously. The first observing mode is a high-resolution imaging camera for measuring non-common path errors and for high-contrast imaging. The second observing mode is a high-resolution long-slit spectrograph. Both are fed by an AO-corrected beam.

Because our main targets are binary stars and standard stars, we need a derotator to keep the field fixed. At the William Herschel Telescope, we use the facility UV/optical derorator. In the next subsections each module of the prototype is discussed, and several design choices for the prototype instrument are described.

## 2.2 Prototype optical design

### 2.2.1 LEXI Adaptive optics system

The adaptive optics module of LEXI was originally designed for ExPo (Rodenhuis et al., 2012). Because ExPo is a polarimetric imager, the AO module was designed to minimize the instrumental polarization. It sits on a customized breadboard at the focal plane of the WHT Nasmyth focus. There a 140 mm lens collimates the beam to a 12.7 mm pupil onto the deformable mirror, an Alpao DM 97-15. The deformable mirror is a high-speed, high-stroke DM with an operating frequency of up to 900 Hz. The stroke of the deformable mirror is 60 $\mu$m, which enables it to remove large aberrations in the system including tipt and tilt introduced by telescope tracking errors and the atmosphere. The beam is redirected by a second fold mirror. The angle that the DM and the fold mirror make with the optical axis were minimized to decrease the instrumental polarization. The beam is then focused by a lens that is identical to the collimation lens. This creates a 1:1 reimaing system between the AO input and output.

A 50:50 polarizing beam splitter with a VIS anti-reflection coating was put in the focus of the AO output beam. This divides the light between the wavefront sensor and the science arm. A polarizing beam splitter was chosen over a non-polarizing beam splitter because the optics in the science arm required a polarized input, and a polarizing beam splitter then provides the highest possible efficiency for the instrument. Due to the geometry of the beam splitter vertically polarized light is sent to the wavefront sensor and horizontally polarized light to the science arm.

A Shack-Hartmann wavefront sensor provides data to the control system. The light from the beam splitter is collimated by a 60-mm achromatic doublet. The collimated pupil of the telescope is then sampled by microlens array. The pitch of the microlenses is 500 $\mu$m, leading to 11 microlenses across the pupil. The images created by the microlenses are then reimaged by a pair of lenses onto an Andor Ixon 870 EMCCD camera with sub-electron read noise and the ability to cool to -80 degree Celsius, which

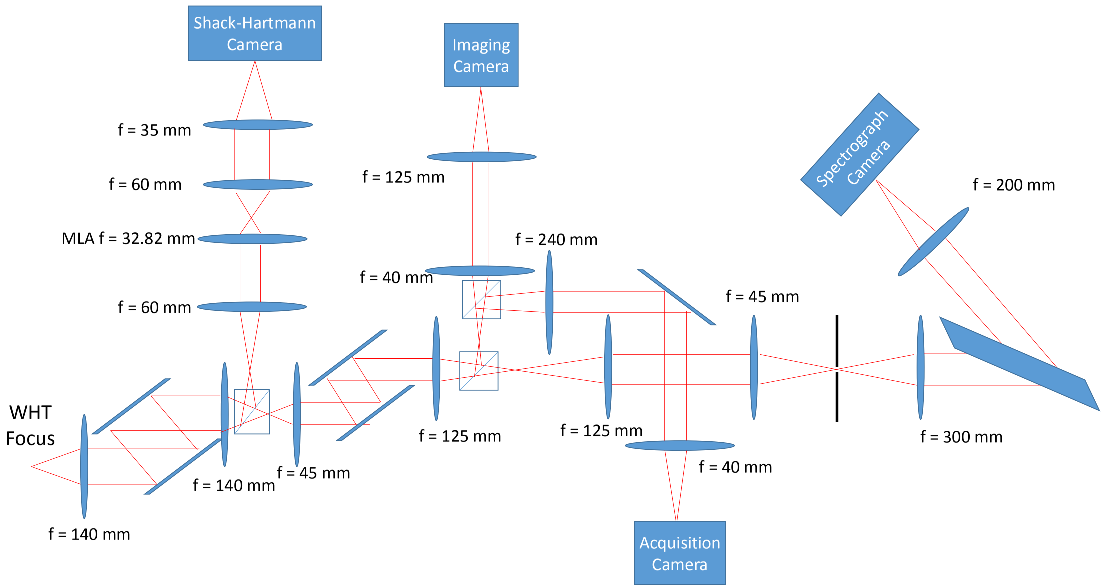


Figure 2.1: A sketch of the LEXI prototype as used at the William Herschel Telescope. The focal lengths of the lenses are shown next to the lens. The instrument can globally divided into three parts. The AO module, the high contrast imaging module and the spectrograph module.

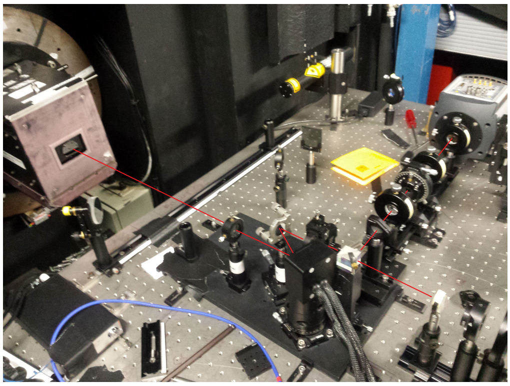

Figure 2.2: AO system as it was set up in GHRILL at the William Herschel Telescope. The red line shows the path of the light.

eliminates dark noise. The camera has 128 by 128 pixels with a 16 $\mu$m pixel size. Each subaperture image is thus sampled by 8 pixels. Due to the size of the secondary mirror of the WHT and partially illuminated subapertures, we could determine 80 useful sub-apertures for on-sky wavefront sensing. The setup of the AO system can be seen in Figure 2.2.

The AO system has two focal planes where spatial filters can be inserted. These spatial filters are used together with an internal light source for calibrations. The wavefront sensor arm is calibrated by using a 10 $\mu$m pinhole in the second focal plane. This creates a point source input for the wavefront sensor. The point source is then chosen as a reference flat wavefront. The reference is necessary for a SHWFS because it measures spot displacements with respect to a certain zero point.

The second part of the calibrations consists in determining the interaction matrix between the deformable mirror and the wavefront sensor. For this calibration we place a pinhole in the first focus as this creates a point source input for the whole AO system. A single column of the interaction matrix is the response to the wavefront mode that is applied to the deformable mirror. The mode response is calibrated by applying the mode with a positive amplitude and a negative amplitude. The difference between these two creates an estimate for the response slope of the mode. Currently the DM can be controlled in an actuator basis, where each actuator is controlled independently, in a Karhunen-Loeve basis or a Zernike basis. The Karhunen-Loeve basis is the standard in which the AO system is operated. Because the alignment of the optical system is not perfect, this calibration procedure needs to be iterated a few times. Each time a new calibration is done, the AO is operated in closed loop to remove the aberrations before a new calibration iteration is done. With this iterative scheme any large aberration that is present due to misalignments of the optics or due to initial non-flatness of the deformable mirror can be removed.

### 2.2.2 Non-common path correction and coronagraph

The second part of the instrument is used for the creation of phase patterns with a Spatial Light Modulator (SLM). The SLM can create phase patterns by applying different voltages to it's pixels. The SLM is a Boulder Nonlinear Systems 512 by 512 SLM XY series with a pixel pitch of 15 $\mu$m and a 83.4% fill factor. Because the SLM is polarization sensitive, it needs to have a vertically polarized input for phase modulation. If the light is not perfectly vertically polarized, the SLM will also create amplitude modulations.

The polarizing beam splitter creates a horizontally polarized input for the SLM. A re-imaging arm was placed between the AO output and the SLM input. This re-imaging arm consists of two identical achromatic doublets with a focal length of 50 mm. A zero-order half-wave plate was placed in the intermediate pupil plane to rotate the polarization from horizontal to vertical. Because the half wave plate is chromatic, there is also a linear polarizer directly after the half-wave plate to filter out any horizontal polarization that could still be present. The orientation of the two components was determined by first inserting the polarizer and minimizing the intensity of the light that came out. That ensured that the polarizer was orthogonal to the polarizing beam splitter. The half-wave plate was then added and rotated until the intensity was maximized. The re-imaged focus was then collimated by a 45-mm focal length achromat onto the SLM. The pupil is then sampled by 274 SLM pixels across its diameter.

The spatial light modulator can be used to create phase patterns for APP coronagraphs (Codona et al., 2006). The APP coronagraphs use phase only pupil functions to apodize the PSF. The apodization creates a dark hole close to the center of the PSF to suppress the diffracted starlight.

One of the largest influences on the performance of coronagraphs are non-common path (NCP) errors. These residual aberrations are not sensed by the wavefront sensor and can therefore not be corrected by the DM. To measure the NCP errors a holographic focal plane wavefront sensor is added to the coronagraphic phase pattern. This coronagraphic modal wavefront sensor(CMWFS) (Wilby & Keller, 2016) creates holographic copies of the PSF that are sensitive to pupil-plane aberrations. For each phase mode

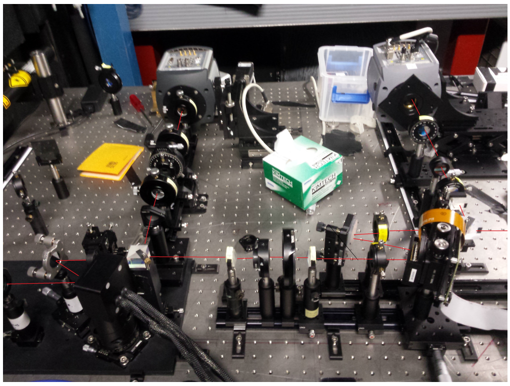

Figure 2.3: In this figure the spatial light modulator configuration together with the high resolution imaging camera are shown. The optical path is indicated with a red line.

two PSF copies are made. The mode coefficient can then be retrieved by measuring the normalized difference between the Strehl ratio of the copies. Because the CMWFS works in the science focal plane, it can correct for any NCP error.

After the SLM the beam was redirected by a fold mirror and then focused by a 125-mm focal length lens. The focused beam goes through a second beam splitter. This 90:10 beam splitter sends 10% to the imaging arm and 90% to the spectrograph. The imaging camera is used to measure the NCP errors with the CMWFS.

To measure the Strehl ratio of each holographic PSF copy correctly, the PSF has to be super Nyquist sampled. A double achromatic lens system magnifies the PSF with a factor of 3.125. With this magnification the sampling is roughly 4 pixels per $\lambda/D$. The camera that is used for the CMWFS is an Andor EMCCD with 512 by 512 16 $\mu$m pixels. The corresponding field of view is about 4 by 4 arcsec on the sky.

Because of the small field of view, it is difficult to acquire targets. Therefore another imaging camera was added. After the second beam splitter a third beam splitter was placed with a 50:50 splitting ratio. The transmitted part is sent to the high resolution imaging camera. The reflected part is sent to an acquisition camera. Before the acquisition camera is a double lens system consisting of two achromatic lenses with focal lengths of 250 mm and 40 mm, respectively. The acquisition camera has a pixel size of 5.6 $\mu$ m and a total array size of 640 by 480 pixels. The field of view of the acquisition camera is about 36 by 27 arcsec. But due to the limited size of the third beam splitter, the field of view heavily vignetted after 30 arcseconds. This effectively creates a field of view of 30 by 27 arcseconds.

### 2.2.3 High-resolution spectrograph

The initial design had a separated path for the SLM and imaging arm and for the spectrograph arm. Because of this the high resolution spectrograph was designed to be fed by a beam with an F-number of 11. This is matched to the output of the AO system. But the module with the SLM setup changed the F number of the beam. So a re-imaging optics was inserted between the spectrograph and the SLM output to create a correct input beam. This re-imaging setup was created with two achromats.

The spectrograph is built around a volume phase (VPH) grating from Kaiser Optical Systems with a line density of 3000 lines/mm. The clear aperture of the grating is 130 mm by 100 mm. This VPH was originally designed for the S5T (Snik et al., 2009) and coated with an UV-VIS anti-reflection coating optimized for 450 nm. With the LEXI prototype we are aiming at the R band. Despite the mismatch between the wavelength range of the grating and LEXI, the VPH grating is usable in the R band. And because the VPH can easily achieve a high resolution because of its high line density we operate it in first order.

There are three parameters that determined the design of the spectrograph. The spectral resolving power, the spectral bandwidth and the entrance slit width. The trade off between resolution and spectral bandwidth was driven by trying to have a bandwidth as broad as possible while still being able to resolve spectral lines. The resolution was set to be 75000 after considering the bandwidth. Together with the spectrograph camera size this results in a bandwidth of 10 nm. The camera for the spectrograph is an Andor Zyla 5.5 sCMOS with 2560 times 2100 6.7 $\mu$m pixels.

The slit width is a dominant component in the throughput of the instrument. The slit width was chosen to be as large as possible while still reaching the spectral resolution of 75000. This led to a slit width of 36 $\mu$m. Since this was not a readily available slit, we used a 30 $\mu$m slit. The effective size of the slit on the sky is 0.13 arcsec. This small slit width was enabled by the adaptive optics system in front of the spectrograph.

Because of the required high resolving power and the high line density, the angle of incidence needed to be quite extreme. The angle of incidence for the central wavelength 632.8 nm is 72.3 degrees. These requirements fixed the focal length of the achromatic collimator and camera lenses, which

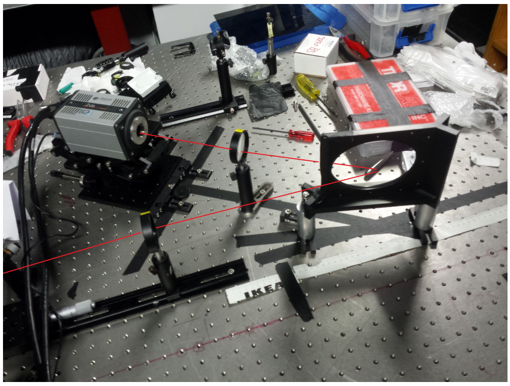

Figure 2.4: The spectrograph as used at the William Herschel Telescope. The red line indicates the optical path. Here the extreme angle of the VPH can be seen.

have focal lengths of 300 mm and 200 mm, respectively.

## 2.3 First light

During June 2016 the instrument saw first light at the William Herschel Telescope. The figures below show the first results from the observing run. The raw spectra have been flat fielded and bias subtracted. No further data reduction has been done yet. In Figure 2.5 the spectrum of Vega is shown. The spectrum of Vega was taken both with AO and without AO. The difference between these two is clearly visible in the figure. The throughput is higher and the extent of the spectrum in the slit direction is also narrower.

A second target was the binary system Zeta Herculis. The visual magnitude of the components are 2.8 for the primary and 5.4 for the secondary. The spectra of the binary are shown in Figure 2.6. Because of the AO the binary is very well resolved, which can be seen in the spectrum in Figure 2.7. Both spectra show spectral lines at the same position, which should be the case since the spectral types of these two stars are close to each other.

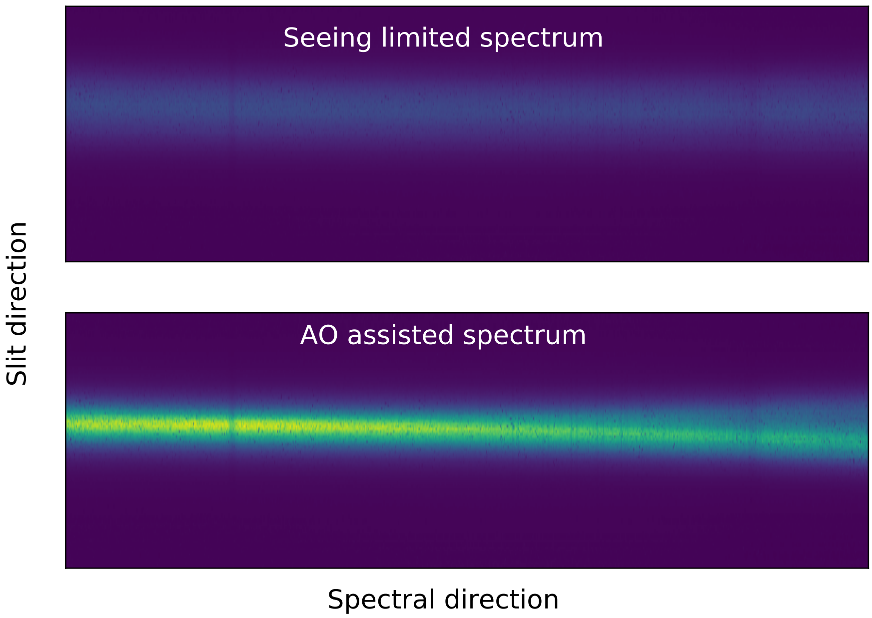


Figure 2.5: Both figures show the spectrum of Vega. The upper spectrum was taken without the AO system, and the bottom spectrum was taken with the AO system. Both spectra were taken with the same integration time. The AO clearly helps with increasing the throughput. Another visible effect is the spread in the spectrum. The spectrum with AO is more concentrated along the slit direction.

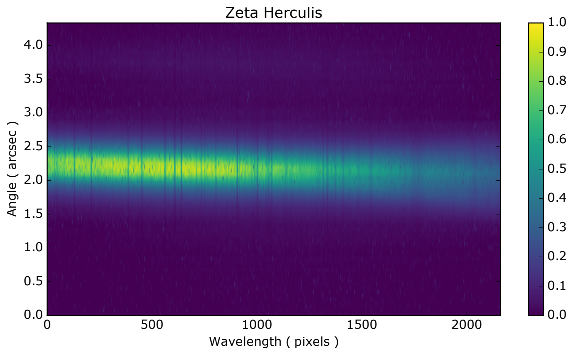


Figure 2.6: Spectra of Zeta Herculis A and B, a resolved binary with primary magnitude of 2.8 and a secondary magnitude of 5.4. The spectrum of the primary is clearly visible and the spectrum of the secondary is quite faint.

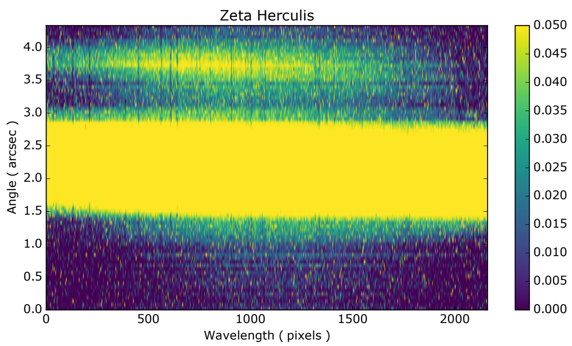


Figure 2.7: Spectra of Zeta Herculis A and B, a resolved binary with primary magnitude of 2.8 and a secondary magnitude of 5.4. This figure is the same as figure 2.6, but the cut of the image is different to emphasize the spectrum of the secondary.

## 2.4 Conclusion and outlook

A LEXI prototype has been built and saw first light at the William Herschel telescope in June 2016. The preliminary data reduction indicates that the prototype is reaching its specifications. A more detailed analysis needs to be done to analyse the on-sky performance.

The current version of LEXI is essentially a narrowband instrument. The imaging arm is working with a narrowband filter in the R band, and the spectrograph has a bandwidth of only 10 nm. Several upgrades are planned to improve the instrument.

The first upgrade is to switch to a broadband system. The most important part to replace is the SLM, because it is highly chromatic. The SLM will be replaced by a liquid crystal phase plate that can be used to create broadband phase patterns (Otten et al., 2014; Snik et al., 2012). The second upgrade will increase the spectral bandwidth of the spectrograph by making a cross dispersed Echelle spectrograph. These two upgrades will enable us to cover the whole visible and very near-infrared part of the spectrum. The third upgrade will add an integral field unit.

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