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Phase A: Calibration Concepts for HIRES

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ABSTRACT

The instrumentation plan for the E-ELT foresees a High Resolution Spectrograph (HIRES). Among its main goals are the detection of atmospheres of exoplanets and the determination of fundamental physical constants. For this, high radial velocity precision and accuracy are required. HIRES will be designed for maximum intrinsic stability. Systematic errors from effects like intrapixel variations or random errors like fiber noise need to be calibrated. Based on the main requirements for the calibration of HIRES, we discuss different potential calibration sources and how they can be applied. We outline the frequency calibration concept for HIRES using these sources.

Keywords: HIRES, Calibration, Spectroscopy

1. INTRODUCTION

The upcoming European extremly-large telescope (E-ELT) will be the first 40m-class telescope. It employs 798 segments of hexagonal shape, creating a primary mirror with a diameter of 39m. Even though designed for superior image quality, its capability of collecting light over a broad wavelength range enables science cases based on spectroscopy.[1] In the current design it is foreseen to change and recoat two elements of the primary mirror every day and the observer will "see" an ever-changing telescope. The 5 mirror construction is designed to be a huge adaptive optic system delivering exceptional image quality at the Nasmyth foci, see "E-ELT construction proposal".[2] The control loops for segments in the primary mirror and M4, a large adaptive optic mirror, are driven by several wavefront sensors. Up to 4 laser guide-stars can be used to measure the aberrations caused by the atmosphere. The telescope is designed to deliver diffraction-limited point-spread-functions (PSF) when

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additional wavefront sensing of the PSF is provided by the instruments behind the Nasmyth focii. The huge Lagrangian invariant, $A \cdot \Omega$, created by the E-ELT is a challenge to all instruments. In addition, the sheer size of the telescope makes it sensible against wind load and the pointing and positioning has to be constantly controlled and realigned. These two effects will be almost but not perfectly compensated, resulting in a *"dancing PSF"*.[3,4] In parallel to the design phase of the E-ELT two high resolution spectrometers, namely CODEX[5] and SIMPLE,[6] have been proposed, aiming for major scientific breakthroughs with the E-ELT. They were merged to one instrument: the high-resolution spectrograph (HIRES). From the flagship science drivers[7] five key science cases have been chosen.[1] From these, the preliminary design for HIRES has been derived. Similarly to other high resolution spectrographs, e.g. SPIRou,[8] ESPRESSO,[9] HARPS,[10,11] CARMENES[12] the instrument needs a sophisticated intensity and wavelength calibration. Two of the main calibration sources will be described in Schaefer et. al.[13] and Charsley et. al.[14] Here, we will outline the concept of the calibration including the calibration unit.

2. SCIENTIFIC REQUIREMENTS AND INSTRUMENTAL DESIGN

2.1 Requirements to the spectrograph

The astrophysical community identified science cases to be carried out with HIRES which have been described in a white paper by Maiolino et. al.[7] These science cases were categorized and prioritized[1] and the requirements for the spectrograph have been distilled. Here we want to summarize only the top level requirements with respect to the science cases:

1. **Exoplanet atmospheres in transmission**
   This science case requires:
   - Resolving power > 100.000
   - Spectral bandwidth: $0.33 - 2.4 \mu m$
   - High spectral fidelity[*] $> 0.1\%$
   - Wavelength-calibration accuracy $< 1 m/s$
2. **Variation of the fundamental constants**
   This science case requires on top of the requirements of science case 1:
   - Spectral bandwidth: $0.37 - 0.65 \mu m$
3. **Exoplanet atmospheres in reflection**
   Additional requirements:
   - Single conjugate adaptive optics (SCAO)
   - Integral Field Unit (IFU)
4. **Sandage-test**
   Additional requirements:
   - Wavelength accuracy $< 2 cm/s$
   - Calibration stability $> 2 cm/s*$
     *This is a relative stability as the integration over 10 yrs over many targets and lines will solve the science case. The absolute stability for each of this measurement is on the order of $1 m/s$.

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[*] With spectral fidelity the precision in intensity measurements is very high over the full spectral bandwidth, this varies with the mag of the respective target.

HIRES will also support a polarimetric mode, as a heritage from PEPSI,[15] which is required for exoplanet atmosphere characterisation and protoplanetary disks as well as the observation of stellar magnetic fields. Thereby, we expect peak amplitudes from an average planet-host star (like the Sun) are $V/I = 1x10^{-3}$ and $Q/I = 3x10^{-5}$ at line widths of down to $4km/s$ (=basically the thermal width). Thus, the requirement is to operate IQUV in differential approach to achieve $dP/P = 10^{-4}$ of a $V = 6^{th}$ mag star. Then, this can be pushed to 12^{th} mag by coadding. Similarly, limiting mag for $dP/P = 10^{-3}$ would be five mags fainter, i.e., 17^{th} mag and five more mags for a 1% limit. Therefore, an observing mode (OM) in HIRES is forseen that will have a resolving power of R=100,000 and an overall system efficiency of 10%.

2.2 Instrumental design of the high-resolution spectrograph

Based on the requirements the HIRES technical team started and by now nearly finished to develop a preliminary design to show how all requirements can be met. In the current phase A study the concept is modular to allow for adjustements. To handle the huge $A \cdot \Omega$ created by the telescope, the baseline foresees the use of fiber bundles that are organized along the slit of the spectrograph unit while are distributed over a quasi-circular aperture at the telescope focal plane. The light will be picked up at the Nasmyth focus in one of the *front-end* (FE) modules, which will be used for different observing modes, see table 1.

Table 1. Overview of the observing modes (OM). All modes will be calibrated before and after an observing run. OM1-OM4 are designed for high throughput and therefore the accuracy is moderate. OM2 and OM4-OM8 allow for observation of two objects, one of these may be calibration light, enabling simultaneous calibration, or the sky to measure the background. OM5-OM8 are designed for high accuracy. OM6 and OM8 employ ”fixed” calibration, which is light fed from the calibration unit (CU) through the fiber-to-fiber-link (F2F) into the spectrographs, see figure 1.

OM	Objects	FOV	Throughput	Accuracy	Fixed Calib.	Res. Power
1	1	$1.4arcsec^2$	high	moderate	No	100,000
2	2 (Obj. + Sky/calib)	$0.68arcsec^2$	high	moderate	No	100,000
3	1	$1arcsec^2$	high	moderate	No	150,000
4	2 (Obj. + Sky/calib)	$0.46arcsec^2$	high	moderate	No	150,000
5	2 (Obj. + Sky/calib)	$0.68arcsec^2$	moderate	high	No	100,000
6	2 (Obj. + Sky/calib)	$0.68arcsec^2$	moderate	high	Yes	100,000
7	2 (Obj. + Sky/calib)	$0.46arcsec^2$	moderate	high	No	150,000
8	2 (Obj. + Sky/calib)	$0.46arcsec^2$	moderate	high	Yes	150,000
9	AO-assisted IFU	$0.5 - 0.0075arcsec^2$	moderate	moderate	No	100,000

In the FE dichroic mirrors are employed to split the light into spectral channels feeding the spectrographs as shown in figure 1. The FE picks up the light from the telescope at the Nasmyth focus and distributes it to the respective fiber bundles thereby creating either a pupil or image slicing.

Depending on the slicing type, the “dancing PSF” creates more or less strong temporal variations in the illumination of the fiber bundles and the individual fibers. In each spectral channel a fiber-to-fiber (F2F) link is foreseen to a) couple light from fiber bundles into new fiber bundles feeding the spectrographs and b) enable shuttering of fibers and c) couple calibration light (fixed calibration) into the respective fiber bundles and d) to obtain the possiblity for modal noise suppression. For high accuracy modes (OM5 - OM8) a near-field far-field exchanger will be used to reduce modal noise. This is a heritage from the positive experiences made in e.g. ESPRESSO.[9] However, influence of modal noise and temporal intensity variations depend strongly on the exposure time, the precision of the position of each fiber in the slit and possible cross-talk between the fibers.

From the F2F fibers carry light into the respective spectrographs. There the fibers are aligned in a slit-like configuration. Inside the spectrographs the pupil of each fiber is imaged onto the CCD via the dispersing elements. The design of the spectrographs is a heritage of UVES, HARPS, ESPRESSO, PEPSI, CARMENES[16] and CRIRES overcoming their individual limitations to match our requirements. Due to the fiber guiding, the location of each spectrograph is relatively free. Since light in the visible and UV regime exhibit strong attenuation in the fibers, so that the two warm spectrographs are situated on the Nasmyth-platform B close to the FE. For the cold spectrographs commercially fibers with low attenuation can be used. Consequently, the spectrographs are

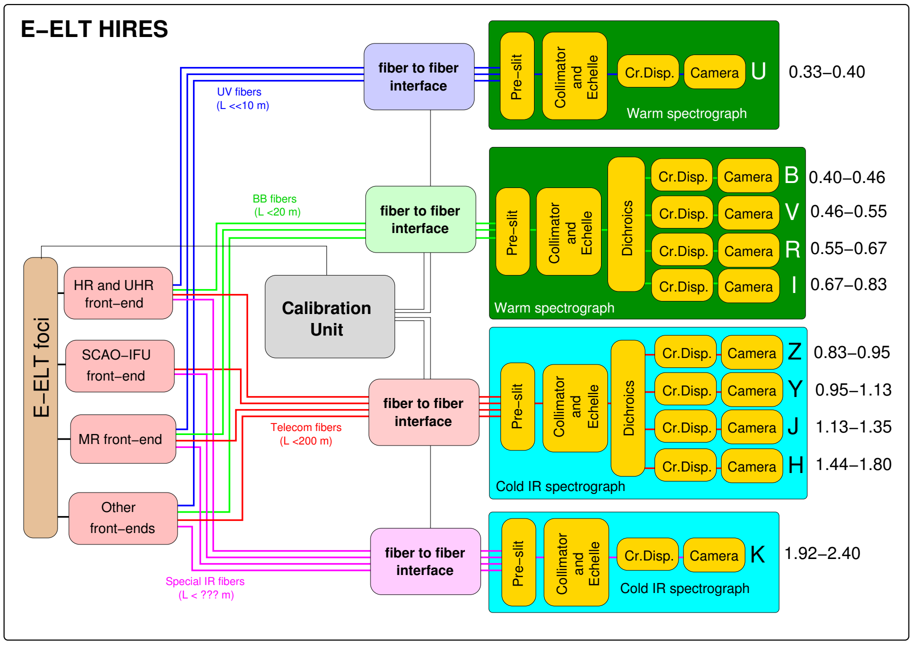

Figure 1. Current architecture of HIRES. The light coming from the telescope is picked up in the Front-Ends (FE). There, the light is split into four spectral fiber "channels". In the fiber to fiber (F2F) interface different operations are possible, e.g. an exchange of the near-field and far-field. From the F2F fibers transport the light into four spectrographs. There, the fibers are aligned in a slitlike configuration. The calibration unit (CU) is connected to the FE as well as to the F2F for "fixed calibration". For the sake of simplicity is the calibration light fed to the Nasmyth focii to visualize that the light from the CU will be used to calibrate each part of the instrument.

located in the Coudé-room, where the environment is much more stable then on the Nasmyth-platforms. The calibration unit will be connected via fibers to the FE and F2F and can be located in the Coudé as well, simplifying the opto-mechanical and thermal design a lot. As a trade off the calibration light has to be transported through long fibers to the FE. However, experience with fiber-fed spectrographs like CARMENES showed that there are always plenty of photons for calibration. The calibration of the polarimeter, which will be located in the optical tower of the telescope, is more challenging. Therefore, fibers will feed light from the calibration unit to the polarimeter.

From the design of the instrument the requirements for the calibration can be derived as follows.

2.3 Requirements to the calibration

Spectra, observed with a spectrograph, are recorded in some arbitrary scale. In the case of HIRES this will be pixels on camera-chips in different optical channels, see figure 1. The spectra must be placed into a calibrated frame, spectral- as well as intensity-wise. This frame is typically provided by spectral reference sources and so called "white light"-sources for "flat-fielding" or intensity calibration.

Thus, calibration requires standards which can be used to compare the measured value against. This requires that these standards can be traced back to values measured with very high accuracy. The difference between the mean of a measured quantity to its true value is its *accuracy*. In the following we will use the phrase *precision* as the standard deviation (when using normal distribution) of a measured value. The transfer of a calibration standard, i.e. GPS-based clocks, to the required optical regime can be done using calibration sources which themselves come with a certain accuracy. The measurement of a (calibration) source against a calibration standard defines it precision. The stability then can be defined as the sum of the accuracy and the precision over a certain time span.

To enable the precision and accuracy over the full spectral bandwidth in HIRES, absorption or emission lines coming from the calibration sources can be used. The optimum distance (free spectral range FSR) between the lines depend on the resolution and on the amount of pixels used per resolution element. It is advantageous that the lines are unresolved by the spectrograph, meaning that the linewidth of each line is much smaller then the instrumental profile (IP). The IP fills the resolution elements. The distance between each unresolved line resembling the center of each IP in the respective resolution element must be high enough, that the IP can be fitted with high precision. As a consequence, the wings of the IP should not overlap and from experience we know that a minimum value used for this spacing is one line every 2.4 resolution element. This defines the minimum free spectral range (FSR) of the calibrators. As the resolving power (R) of the planned echelle-spectrograph does not vary over the spectral bandwidth the required FSR varies. Using the definitions the requirements for the calibration (all science cases) are:

- Calibration of the spectral intensity precision and stability of the spectral response of the whole instrument
- High spectral accuracy modes require ”simultaneous” calibration using either one of the two object channels, see table 1
- Fixed calibration for OM6 and OM8
- Spectral bandwidth: $0.4 - 1.8\mu m$ (goal $0.37 - 2.4\mu m$)
- Every 2.4 resolution elements one unresolved spectral line
- Spectral accuracy $< 1m/s$ (goal better than $10cm/s$)
- Spectral precision $< 10cm/s$ (goal better than $1cm/s$)
- Calibration stability $< 1m/s/year$
- Spectral fidelity $< 0.1\%$
- Intensity precision $< 0.1\%$

Typically, when creating a source for calibration, a calibration unit, we aim at values a factor of 10 better for the accuracy and precision as for the full instrument. This is due to the fact, that the light coming out of the calibration unit is affected by the light guiding to the instrument and by the instrument itself. To disentangle the effects caused by the light guiding and the different components of instruments the calibration unit has to be independent of the instrument.

To show how to achieve this and to fulfill the requirements above we designed a calibration unit, which will be detailled in the following section.

3. CALIBRATION UNIT

The preliminary design of the calibration unit (CU) aims to fulfill all the top level requirements and many technical ones, like size, weight, power consumption, command or even costs. It will consist of sources for the calibration of the intensity and the wavelength of each resolution element of the large bandwidth of HIRES. Due to the challenging requirements and due to technical necessity it employs a compact and robust Fourier-Transform Spectrograph (FTS). This makes the CU independent of the instrument itself, allowing e.g. for the creation of a wavelength solution inside the CU. This can be used to track down any longterm drifts of the instrument.

3.1 Intensity calibration sources

Intensity calibration by acquiring flat fields delivers important information about the system. Due to the sheer size and to the daily operations dome flats are out of question by now. In addition the adaptive optics of the telescope would not work properly without true point sources and laser guide stars. As a consequence the spectral response of the telescope has to be estimated or calibrated with a very well known star. Since the intensity calibration can not be simultaneous to the science observation, the intensity calibration can be done when the instrument is ”offline”, not connected to the telescop. Therefore, light from the intensity calibration sources is fed from the CU to the focal plane at the Nasmyth focus. There the light is reflected into the FE onto the path of the science light.

The following intensity calibration sources are foreseen:

1. Laser Driven Light Source (LDLS)
   The LDLS has a flat spectral emission profile despite of some peaks in the region around 830 nm, see figure 2. There are some features, but it can be used throughout the U,B, V, R, I bands. In the IR it can be used for the Y, J, H bands,but it has to be calibrated thoroughly. From experience we know and the manufacturer recommends that the LDLS has to be flashed with Nitrogen every once in a while to maintain its spectrum. A LDLS is employed as a flat-field lamp in SPIRou[8] and ESPRESSO.[9]
   The total precision of the standard used in the measurement is below $+/-2.0\%$ from $330-1300nm$.

   - Advantages
     Life time$> 9.000h$
     Flat spectral irradiance from $380-780nm$
     Typical spectral irradiance is 10^2 larger then for Halogen lamps
     Fiber coupled
   - Disadvantages
     Output power reduces $1\%-2\%$ per 1000 hours
     Expensive
     Needs constant Nitrogen flashing

2. Halogen lamps
   Halogen lamps are used in many astrophysical instruments (e.g. CARMENES[12]). Since they are black-body - radiators their spectrum is continous with only few lines.

   - Advantages
     Continuous spectrum
     Low cost
   - Disadvantages
     Spectral intensity varies over two orders of magnitude in the visible
     Low intensity below $400nm$
     rel. short Life time$> 2.000h$ Not fiber coupled

3. Light Emitting Diodes (LED)
   LED are available at nearly every spectral region, typically with a narrow bandwidth of max. 200 nm. However, their spectral stability, low cost, high efficiency make them a promising solution[†].

   - Advantages
     Moderate cost
     Long life time (most of them)
     Continuous spectrum
     Low power consumption (most of them)
   - Disadvantages
     Narrow bandwidth - many of them have to be used
     long term behavior not known sufficiently

4. Light bulbs
   Light bulbs are natural heaters and very often heat their glas-body to a high temperature, that they can be used as intensity calibrators in the K-band (internal communication with U. Seemann on the CRIRES CU). However, they are short-lived and not very stable.

The aim is to create a level spectrum with as minimum as possible variations, one light source would be desirable. Since none of the sources cover the full bandwidth, a combination has to be used. It is also desirable to use the light of the intensity calibration sources for illumination of the Fabry-Perots (FP). Due to this the light of each

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[†] see e.g. $http://www.ibsg-st-petersburg.com/led\_1HP.html$

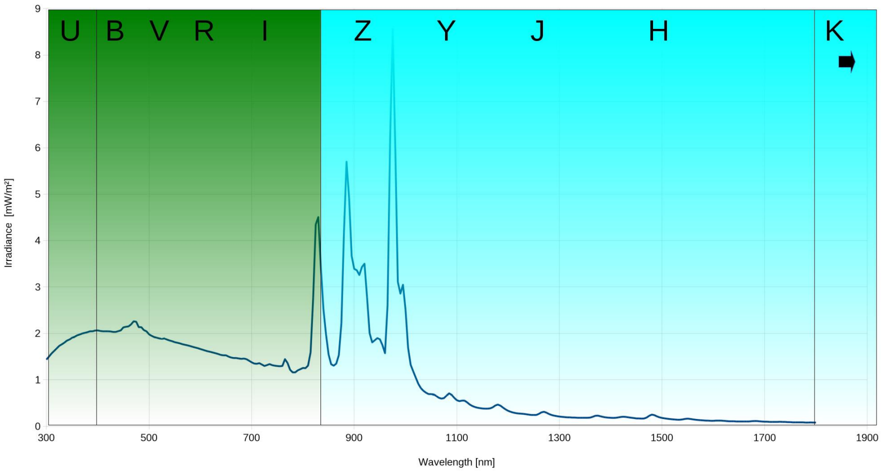

Figure 2. Spectrum of a Laser Driven Light Source (LDLS), calibrated Halogen-Lamp (cHL), a LED and xx.The resolution of the LDLS-spectrum is 5 nm. The uncertainty of the reference standards used in the measurement of the LDLS-spectrum are quoted by the PTB (Irradiance standard 17224/1). For the spectrum we like to thank cordially S. Gunnell (energetiq, LDLS).

source will be used in at least four ways (two FE, FP and the FTS). Some of this light travel through fibers from the Coud-room to the FE and down in the spectrographs, seeing a lot of attenuation. However,the current design efficiency of the instrument can be used to estimate the amount of light needed and even a weak LED would be enough in most of the cases. (Limiting the minimum observation time).
Since the wavelength-dependent precision and accuracy relies strongly on the observation time and the sensitivity of the detector each intensity calibration source will be measured with the FTS inside the CU. This allows us to measure the absolute spectral response of HIRES and to minimize the precision of the intensity of each pixel. The intensity of each source will be controlled using filters with varying optical density as in ESPRESSO.[9] This enables adaption to the observing time as well as small scale variations to test the spectral sensitivity and precision of HIRES at each intensity level.

3.2 Spectral sources

In the case of todays high resolution spectrographs, the product of the wavelength calibration process is the wavelength solution, i.e. a bijective function $f(x, y) = f(\lambda)$ which assigns to every position (x, y) on the sensor a single wavelength λ. In the case of a multi-fiber-fed spectrograph like HIRES each fiber Φ has its own wavelength solution, which results in a more complex function $f(\Phi, x, y) = f(\lambda)$. To achieve this, we remind here the properties of the ideal calibration source:

1. Covering the full wavelength range of the spectrograph
   Even though it is possible to generate a wavelength solution out of a few “supporting points”, it always reduces the precision.

2. Line position and shape stability of ALL lines is better than TBD m/s over the instrument life-time
   Conventionally, the positions of the lines used for calibration are measured in a laboratory before the CU is used with the spectrograph.

3. Lines are not resolved by the spectrograph
   Otherwise information is lost, respectively we do not take full advantage of the spectral resolution of the instrument. Also, narrow calibration lines are NOT distorted by the finite instrumental profile (IP).

4. The line separation is perfectly stable and analytically defined
   There should be no free parameter in the line position, i.e. the accuracy of each line position is as very high. Ideally, the lines are equidistant.

5. The line separation must be minimum 2 and maximum 4 FWHMs of the spectrograph IP to avoid blending and well-sample the pixels.

6. The relative intensity of any neighboring lines must be stable at over the full integration time of at least one observation.

7. The dynamic range of line intensities must be within the linear dynamic range of the detector (in case of a CCD)
   If not, regions of the detector will be saturated. These regions may not be used later on. In the worst case, overspilling takes place which may contaminate even more regions.

8. The overall intensity must be adaptable
   It is often necessary to acquire calibration light as long as the observation time. This accounts especially for the simultaneous calibration.

9. The degree of coherence and polarization of the calibration source and light coming from the science object should not differ too much
   Coherence affects the light distribution on every surface and in each fiber. Light with high temporal coherence (high brilliance) may be focused to a much smaller volume. For example, on a CCD the focal point of a laser source may be a fraction of a pixel, while incoherent light covers a few pixel. This affects also the noise which is generated in fibers. Coherent light tend to show relatively low-frequency modal noise, while incoherent light shows significant high-frequency modal noise. Since all reflecting surfaces show polarization-dependent reflection, the spectral response of an instrument depends on polarization. This is somehow reduced when using fibers scrambling the state of polarization to a certain degree.

To comply with all these requirements a mixture of calibration sources and procedures to use them consecutively has to be developed. The procedures are explained section 3.4. The following sources are foreseen to be used in HIRES:

1. AstroComb(s), detailled description in[14]

2. Fabry-Perots (FP), detailled description in[13]

3. Single wavelength Laser

4. Hollow-Cathode Lamps (HCL)

3.2.1 Astrocomb

Astrocombs are based on laser frequency combs, which produce a series of equally-spaced lines in the spectral domain. As a consequence they have been regarded as the ideal calibration source for astrophysical spectrographs. In the publication of Charsley et. al.[14] an overview of astrocombs already employed in other spectrographs is shown. In addition, the challenges arising with this technology are discussed some. Charsley et. al.[14] describe in a greater detail our approach for a broadband astrocomb. Here, we want give an overview on the approach, see figure 3, and describe how it can be implemented into the calibration concept for HIRES.

The comb is based on a robust, turn-key 1-GHz-Titanium-sapphire laser. These lasers are commercially available and thus become feasible in costs and easy to handle. Stabilization of the carrier-envelope offset frequency (f_{CEO}) will be done in a common-path f-2f interferometer.[17] The light will be split into three channels, where it is converted into different spectral regions. Spectral broadening is achieved with nonlinear fiber. The comb filtering is done with up to six FP. The free spectral range (FSR) and the Finesse (F) of the Fabry-Perots are design parameters, see table 2.

The Finesse F defines the $FWHM = FSR/F$ of the FP modes. The modes must be narrow enough to provide sufficient suppression ($> 30dB$) of the unwanted comb modes. Due to dispersion[18] the comb modes will not be centered inside the FP modes, so that the width of the modes define the spectral bandwidth in which the optical filter can be used. The final design of the FP will also rely on the dispersion of the active optical

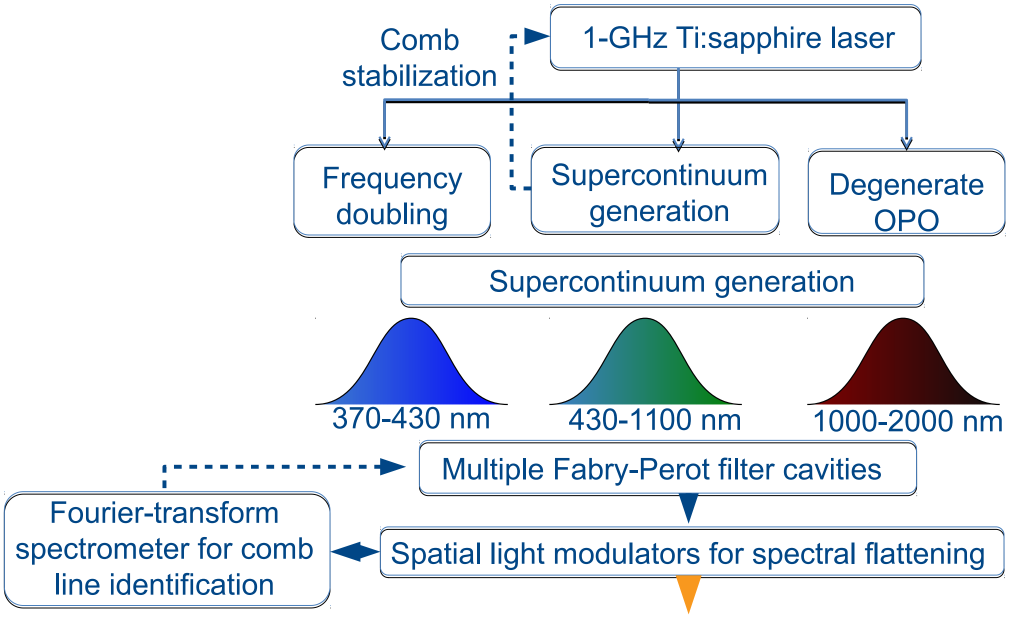

Figure 3. Approach for a single, broadband AstroComb by R. McCracken (HWU). The source will be a 1 GHz Titanium-sapphire laser. The laser will be split up into three arms, a) a frequency doubling, b) a supercontinuum generation with f_{CEO}-stabilization and c) degeneration in an OPO. The light of a) and c) will be send into the nonlinear fibers for supercontinuum generation. Currently, six Fabry-Perots are foreseen to filter the comb to the required FSR, for more details see text. The spectrum will be flattend using spatial light modulators. The FTS is used for comb line identification and in the feedback-loop of the spectral flattening.

Table 2. Configuration of FP for optical filtering the astrocomb. The FSR is optimized for each FP to come as close as possible to the value of 2.4 resolution elements/line for the blue end of the respective spectral bandwidth. The Finesse F is a design parameter. Details see text.

No.	$\lambda - \lambda$	FSR	F	Res. Elem./Line
1	375 - 435 nm	20 GHz	153	2.4 - 2.78
2	435 - 515 nm	17 GHz	153	2.4 - 2.84
3	515 - 630 nm	14 GHz	153	2.4 - 2.94
4	815 - 1155 nm	12 GHz	153	2.4 - 3.10
5	630 - 815 nm	9 GHz	153	2.4 - 3.40
6	1155 - 2000 nm	7 GHz	153	2.4 - 4.16

elements, i.e. the mirrors.

At every initialization of the astrocomb the FP have to be adjusted to the comb-modes. In order to optimize throughput and to always transmit the same sub-set of comb-modes the FTS, explained in subsection 3.3, is used. The spectral flattening will be done as demonstrated in Probst et al.[19]

Although our approach for a broad-band astrocomb covers almost all of the properties of an ideal calibration source, it just fails the last point (9) of the list in section 3.2. As a consequence the spectral response of the instrument will differ slightly for the astrocomb's light compared to the science object's light. During high-accuracy observations (OM5-8) the light of the astrocomb will see a comparable path as the path the science if it is used in the second channel, see table 1. The light will pass the double scrambler inside the F2F, which shall reduce the modal noise. The modal energy distribution of a coherent light source like the astrocomb is much more stable then the of a temporal incoherent source. As a consequence the modal noise will be in a different, lower frequency regime then the modal noise of the science light. In turn the light of the astrocomb never fills the modal volume of the multimode fibers as a incoherent light source does. The imaging of the pupil inside the spectrograph may reduce these effects. However, spurious interference effects inside the spectrographs may cause additional noise. The light of the astrocomb is strongly polarized, causing also modulation effects on the envelope of the spectrum via the non-linear Kerr-effect inside the fibers.[20] Since this is slowly varying effect, this might be of no consequence to the observation. Still, this is part of current investigations.

However, the light of the spectrally-flatened astrocomb still follows a nearly perfect shah-function and will be used for determining the wavelength solution of HIRES.

3.2.2 Fabry-Perots

Fabry-Perots (FP) proved to be a valid solution for relative calibration of astrophysical spectrographs, because they are easy to use, they produce a comb-like spectrum and they are much cheaper then astrocombs. However the properties of the emitted spectrum depends strongly on the degree of polarization and coherence of the input light. Typically, they are used with stable light sources, like those described in section 3.1. Fabry-Perots (FP) are currently employed in e.g. HARPS,[11,21] ESPRESSO,[9] CARMENES[12,22] and will be employed in CRIRES+ (U. Seemann internal communication), FERROS (S. Schaefer internal communication) and many more spectrographs. An overview on FP will be given in our subsequent publication by Schaefer et. al.[13] Also, there will be discussed the current design of the FP foreseen for HIRES. Here, we only want to outline the approach and how they can be implemented into our concept of calibration.

To fulfill the requirements to the spectral calibration sources, see 3.2, the following free parameter can be chosen:

- Type of FP, conventionally plan-plan mirror configurations are used, other, even unstable configurations may become feasible
- FSR, needs to be adapted to the requirement to have every 2.4 resolution element 1 line, varies with the dispersion of the FP
- $FWHM$, defines the throughput of the FP, the peaks need to be narrow enough to become unresolved by the spectrograph
- Spectral bandwidth, depends on the mirror reflectivities, their dispersion and the dispersion of the FP
- Control, active by means of a feedback loop or free-floating (passive)
- Coupling, free space or fiber
- Enclosure, using a thermally stabilized, vacuum-pumped tank as in CARMENES[22] or free space
- Operational mode: Reflection / Transmission

Most of the parameters are interrelated and can not be chosen freely. E.g. different types of FP have different mode degeneration and thus influence the FSR. As already outlined in the previous section 3.2.1, the FSR and the $FWHM$ define the spectral bandwidth of the filtering FP via the apparent dispersion. For a set of FP, illuminated by the respective intensity calibration source, the dispersion governs the design. For high accuracy OM the FP have to be stable during observations, i.e. $10cm/s/night$, if they can not be calibrated otherwise. So, if passive devices will be used, they have to be fiber coupled immersed in a thermally stabilized, vacuum-pumped tank. Actively controlled devices don't need the tank but require a feedback loop. In case of the filter FP of the astrocomb this may be done by dither-locking.[14]

As a consequence two possible configurations can be chosen for HIRES:

1. Two sets of FP, one for filtering the astrocomb, one as separate calibration sources
   Two sets of FP relax the design. The parameter for both sets can be chosen independently. The set for direct illumination can be passively stabilized and even their bandwidth can be increased to reduce the number of FP. The main advantage of having fewer FP are less overlapping regions of their bandwidth.

2. One set of FP, using the filtering FP of the astrocomb as calibration sources
   One set reduces the amount of optical devices. Since the parameters FSR and $Finesse$ for both sets seem to converge, one set may be enough. The advantage is, that we can use the dither locking for the FP within a small spectral range (i. e. 1 nm) and still achieve a stability better then $1m/s/night$. On the other hand the optical routing becomes more complicated.

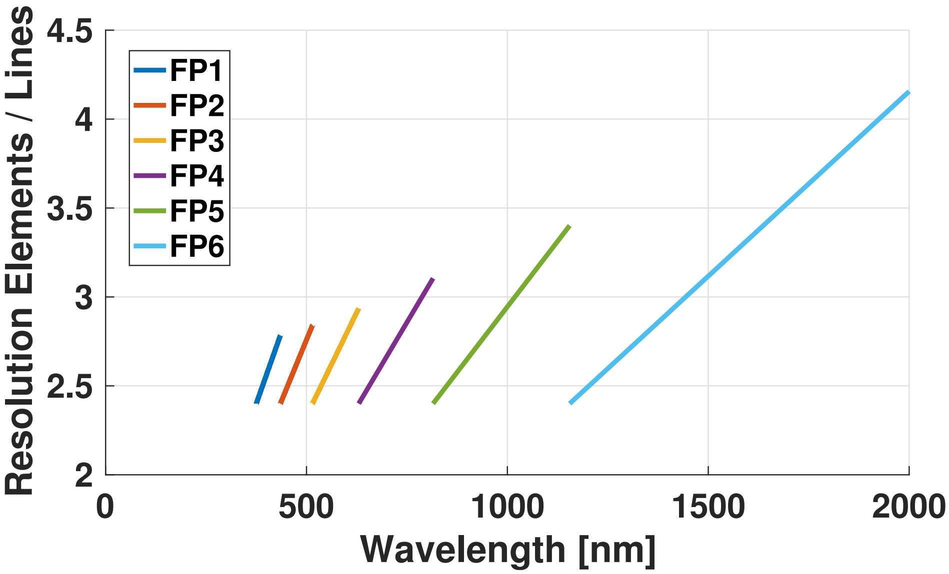

Figure 4. Resolution element per lines for all six FP used for comb-filtering. The FSR of each FP is chosen to start with one line every 2.4 resolution elements, a bit smaller as in table 2, where the FSR has to be a multiple integer of the initial comb FSR (1 GHz). The distance between subsequent FP modes increases in wavelength range.

A more detailled discussion is given in.[13] Both configurations provide FP in transmission and reflection with sufficient stability. However, the current baseline is to use two sets of FP to free the design parameters.

3.2.3 Hollow-Cathode Lamps

Hollow-Cathode lamps (HCL) have been and are successfully employed as sources for fine line spectra which are well suited for calibration of spectrographs.[23] The large number of narrow metal lines and even the broader gas lines have stable wavelengths. Since the spectrum shows virtually no background the S/N of each line is often very high. The metal lines are used for calibration of high-resolution spectrographs which carry out radial velocity surveys like HARPS, ESPRESSO or CARMENES.[24] But the HCL emit also light from the buffer gas which is often much stronger then the light coming from the metal lines. The gas lines are too broad to be used in these high-accuracy measurements and therefore pollute the calibration spectra. In case of an echelle-spectrograph and a CCD they can even render whole orders useless or spill over into other orders.
Crucial to high accuracy calibration with HCL is the ratio of the gas- to metal-lines[25] which depends on the light coupling[26] and the driving current,[27] which in turn influences the life time of the respective HCL. While former surveys often employed Thorium-Argon (ThAr) HCL, CARMENES mainly uses Uranium in combination with Argon (UAr) and Neon (UNe). For all elements fine catalogues are readily available.[28–30] With these catalogues and reference spectra measured with a high resolution Fourier-Transform Spectrograph (FTS, Bruker IFS125HR with 2m arm length), CARMENES reached a precision of 1 m/s in its visible channel (A. Reiners, internal communication).
The main disadvantages of HCL are their limited lifetime ($< 6.000h$), the disturbing gas lines and the uneven distribution of lines that can be used for calibration." . However, they provide a feasible, robust fall back solution and may be even feasible for OM 1 - 4, the high throughput modes, where no high RV-precision is needed. As a consequence the CU will contain UAr-, UNe- and other HCL which may extend to the infrared. Experiments are foreseen with iron (Fe) as cathode-material and Xenon as buffer gas might be of interest for the UV (U-channel).

3.2.4 Single Wavelength Lasers

Lasers have been proven to be the most stable wavelength sources available since many years. The Laser frequency comb described in section 3.2.1 is only the last example. To date there exist for nearly every wavelength from the UV to the IR lasers, most of them are expensive, large, difficult to stabilize and require often an own wavemeter for the control loop. One type of sources are the diode lasers, which are cheap, easy to control and readily

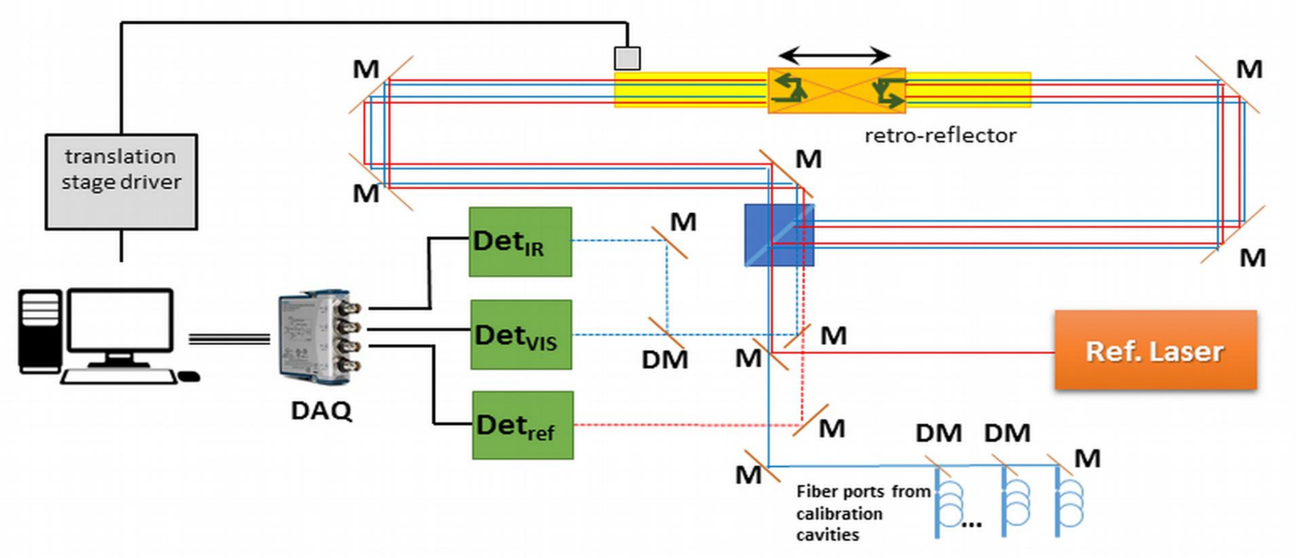

Figure 5. Design of the Fourier transform spectrograph (FTS). The translation stage is shown as a yellow rectangle. M mirrors, DM dichroic mirrors, DAQ data acquisition board, Det_X optical detectors working in the appropriate spectral ranges, Ref_{laser} reference laser(s).

available with feedback loops. They can be swept mode-hop-free over several GHz and with mode-hops they can be tuned over $40nm$ and more. Swept sources are not of interest in the current design in HIRES but they can be interesting in near future.

One of the big advantages of diode lasers are, that they come with a narrow linewidith and low short-term drifts when not locked to a standard. Thus, they can be used to identify single wavelengths. Thus, they can be used to identify single wavelengths, as well as as a fiducial marker to identify the comb line of the astrocomb. However due to te broadband coverage of HIRES, multiple highy stable lasers would be required, therefore we propose an alternative solution based on FTS in the whole spectral range.

3.3 Fourier-transform spectrograph

As mentioned in the subsection 3.2.1, the astrocomb design will adopt the scheme described by Charsley et al.[14] The 1 GHz optical frequency comb will be filtered to the required spacing between astrocomb modes (in the range between 6 and 19 GHz, as shown in table 2) by FP with appropriate FSR. Thanks to Vernier filtering,[31] only a subset of comb modes will be transmitted through an FP, but this will cause an ambiguity in the modal-subset transmission. A common approach to identify the filtered modes[32] is to use a continuous-wave laser of a known frequency - either locked to a molecular or atomic transition or referenced to the unfiltered stabilized optical frequency combas a reference and compare it with the filtered comb. However, since HIRES requires broadband astrocombs, this option is not viable due to the high number of FP cavities needed for filtering, limited operation of cw lasers and limited number of traceable atomic/molecular transitions in the whole required spectral range.

Therefore, we propose an approach based on an FTS, which provides a way to perform spectral measurements and modal-subset identification in the whole spectral range with a single device. The design of the spectrograph with the folded arms is similar to previous works[33,34] and is shown schematically in figure 5. Light coming from the filtering FPs will be combined into a single beam and fed to the FTS. The optical path length will be calibrated with the reference cw laser (which can be absolutely stabilized to the OFC or to an atomic transition[34]). All-metallic optics will enable the broadband operation of the system, with dichroic mirrors used for beam combining at the input and beam splitting the output of the spectrograph. The interferogram detection will be split into three separate channels: one for the reference laser beam - using a Si detector shown as Det_{ref} in figure 5; and two for filtered-comb beams. The comb beam detection in the visible and near-IR range will be done with an Si detector, DetVIS, and in the IR rangewith an InGaAs detector, Det_{IR}. If needed, a balanced detection scheme[34,35] will be employed for higher sensitivity. Signal acquisition will be performed by a fast digital-analog converter with high vertical resolution (16-bit or better), which is essential for the detection of broadband signals characterized by high intensity interferograms. As was shown previously, the transmitted comb subset can be identified if the frequency resolution is several times better than the filtered comb mode-spacing (approx. 10 times in[34]).This requirement implies that the length of the translation stage will have to be in a few tens of centimeters range for the astrocomb spacings shown in table 2. Alternatvely, the recently developed approach to comb-based FTS measurements providing optical resolution not limited by the optical path difference (so called sub-nominal resolution)[36, 37] can be employed. Due to the well defined structure of the optical frequency comb, the intensities and absolute positions of the comb modes can be measured very precisely without the influence of the instumental function of the spectrometer. The optical path difference is required to be finely tuned to be an integer multiple n, of c/f_{rep}, where c is the speed of light and f_{rep} is effective repetition rate of the filtered comb (i.e. the spacing between the astrocomb modes). When n is choosen to be ≥ 2, the transmitted comb mode subset can be identified with shorter optical path difference than in the previously mentioned approach, which translates to a smaller size of the spectrometer and a shorter acquisition time.

3.4 Wavelength and intensity calibration inside the Calibration Unit

The Fourier-Transform spectrograph (FTS) described in the former section 3.3 is foreseen to identify the astrocomb lines. With the reference laser(s) the optical path is calibrated as well as it can be used for comb line identification. This constrains the free parameter of the astrocomb, since f_{rep} and f_0 will be determined and controlled otherwise.[14] In addition the single wavelength lasers, used for all spectrographs can be measured in parallel with the astrocomb.

The FTS can be also used to determine the lines of each FP, either if there are two sets of FP or one set. Even though the accuracy of the FTS on each FP mode may not be high enough, the precision, coming from the large amount of modes will be below $1cm/s$. This allows to measure the performance of the FP even during observation of a science target with HIRES in simultaneous calibration mode, see OM4-OM8 in table 1. The resolution and sensitivity of the FTS may not be high enough to measure the hollow-cathode lamps.

However, the spectral intensity response function of the FTS will be gauged before bringing it into operation. This allows to determine the spectral intensity distribution of each calibration source with high accuracy and with subsequent measurements also high precision.

3.5 Combination of sources inside the Calibration Unit

In the previous section we described which calibration sources are foreseen for HIRES. They must be combined inside the calibration unit (CU). The current baseline to place the CU inside the Coudé-room allows to use optical tables. This simplifies the optomechanical setup. In figure 6 is given a preliminary sketch of the optical paths inside the CU. It is only done for one FP to outline the idea.

The light of the intensity calibration source (ICS), see section 3.1, in figure 6 is incident on the first beam splitter ($BS1$) which splits the light into a transmitted and reflected part. How much light is allocated to which part is to be defined. If the shutter (BB) is open the transmitted light is coupled into an octagonal fiber (OF) which guides the light into the light distribution point (LDP). Inside the LDP the light of the sources will be combined and intensity controlled via optical density filters as it is done in ESPRESSO. The LDP distributes the light to the two front-ends (FE), to the *polarimeter*, to the $F2F$ for fixed calibration and to the FTS inside the CU.

The reflected light from $BS1$ is filtered by wavelength with the $BS2$. The range depends on the choice of the parameters of the FP, see section 3.2.2 and will be defined in phase B. Figure 6 shows the case where the astrocomb is already filtered and used for active control of an indipendent FP. Therefore, only a fraction ($1nm$) of the astrocombs spectrum is fed into the FP. Incident on an other port of $BS2$ is light coming from the astrocomb, see section 3.2.1 and the single λ laser, see section 3.2.4. The light transmitted by $BS2$ (downwards in figure 6) of the ICS and the reflected part of the astrocomb is filtered by the FP. $BS5$ will have the same properties as $BS2$, so that the light of the astrocomb is reflected into one of the power detectors $PD4$. The light of the ICS filtered by the FP is fed into the LDP using the fiber coupler 4 ($FC4$). Incident on $FC1$ is the light reflected by the FP. Into $FC3$ is coupled the main part of the spectrum of the light coming from the astrocomb and the single λ laser.

The power detectors allow to measure the intensity of the astrocomb ($PD1$), the by the FP reflected $PD3$ and

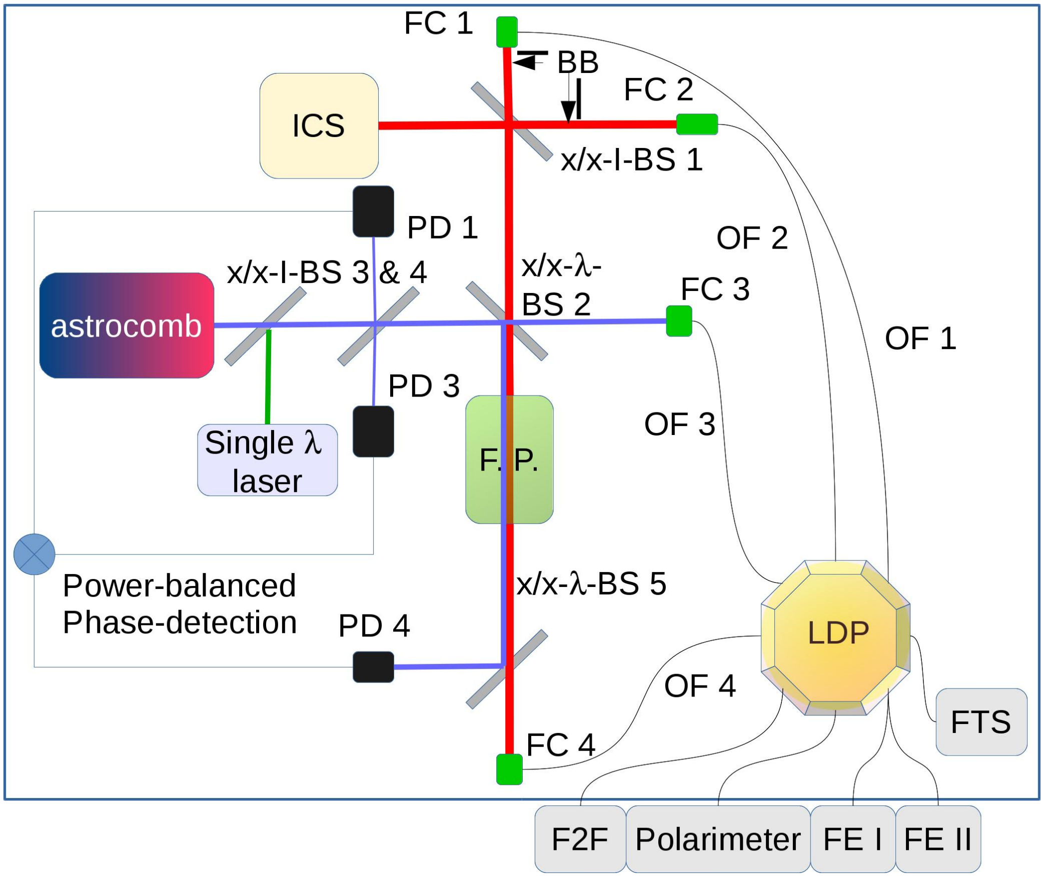

Figure 6. Sketch of the optical paths of the intensity (ICS) / wavelength calibration light sources (astrocomb, Single λ laser) inside the calibration unit (framed box). With the following acronyms: ICS := intensity calibration source, FC :=fiber coupler; BB :=shutter; $x/x - I - BS$:= intensity beam splitter with $x\%$ transmission/reflection; $x/x - \lambda - BS$:= wavelength beam splitter with $x\%$ lower/upper wavelength limits; PD := photo diodes or power detectors; OF := octagonal fibers; $F.P.$:= Fabry Perot (FP); LDP := Light distribution point; FTS := Fouriertransform spectrograph; $F2F$:= fiber to fiber link; FE := front end. The sketch shows only the paths for one FP. The power-balanced phase-detection is used for the error signal of the dither locking. More details see text.

transmitted $PD4$. By modulating the length of the FP within a range of a few kHz, the transmitted and reflected intensity will vary. After power balancing this signal can be used as an error signal for the control loop.

3.6 Summary

In this section we described which crucial elements will be used in the calibration unit (CU) and outlined how they can be combined. With the different calibration sources we will be able to fulfill all requirements to the CU. With the FTS we are able to provide a daily, absolute wavelength calibration inside the CU, making it an independent instrument on its own. Wavelength anchors are the reference lasers inside the FTS, which also may be used as fiducial markers, and the GPS-disciplined quartz inside the f_{rep}- and f_{CEO}-control loops of the astrocomb. The transfer of the wavelength solution inside the CU to each spectrograph of HIRES will be done using the astrocomb and fiducial markers for constraining the free parameter in the astrocombs spectrum, i.e. mode numbers will be determined. The measurement of the spectrum of the intensity calibration sources with the FTS allows us to track down changes in the throughput of HIRES. In the following section, we will outline how the different sources maybe used; how the calibration procedures may look like.

4. CALIBRATION CONCEPT

The conceptual design of the calibration unit (CU) is based on the requirements to the spectrograph. Even though the design of the spectrograph may change, the CU remains its functionality. However, data reduction steps which may be necessary are not part of this work. This also accounts for dark images and how many flat fields have to be taken. However, the instrumental design already foresees a range of observing modes (OM), see section 2.2 and different procedures for frequency calibration can be outlined. How the light from the CU is distributed to the Front Ends (FE) and to the fiber to fiber (F2F) links is shown in figure 1. There are different options how to use the calibration sources.

The option which will be discussed in this publication foresees the astrocomb to be used to find the preliminary wavelength solution. For simultaneous calibration the Fabry-Perots (FP) will be used. One of the advantages of this scheme is that, in combination with the single λ lasers and the Hollow-Cathode lamps (HCL), this enables back-up schemes if one of the sources (FP or astrocomb) fails and require maintenance.

There are two types of calibration, *"offline"* (during times without observing science targets) and *"simultaneous"* (simultaneous to science observations).

OM1-OM4, the high throughput modes, require only offline calibration. For OM4-OM8 simultaneous calibration is required. In these modes two FE will be used, one observes the science target and the other may be used for sky subtraction or for calibration. In addition OM6 and OM8 allow for fixed calibration using the light path from the CU directly into the F2F.

4.1 Offline calibration

Due to the fact that several instruments will be in operation at the E-ELT at the same time, HIRES will not make scientific observations every night. This increases the amount of "offline" times, where the instrument does not "see" the telescope. This time will be used for measuring the performance of HIRES with regard to throughput and drifts.

4.1.1 Intensity response function

For the offline intensity calibration the intensity calibration sources (ICS) will be used. The following steps can be done to achieve a high intensity precision in each resolution element of HIRES:

1. Warm up of the ICS until point of stable operation is reached
2. Adjust the intensity of the ICS inside the CU according to the requirements of the next observations (integration time during one observation)
3. Measure spectrum with the Fourier-Transform spectrograph (FTS) and in parallel
4. Guide the ICS light to FE I / FE II / fixed calibration
5. Measure the flat field with HIRES as often as needed to create a flat field with high precision
6. redo step 3 - 5 until each light path is calibrated
7. redo step 4 - 6 with blocking light of individual fibers (shutter in the F2F) to obtain the performance of each fiber
8. Calibrate spectral response function of HIRES
9. Track down long-term drifts by comparing the spectra obtained with the FTS and HIRES

Step 7 and 9 are not necessary every time. However, they provide information how the performance of HIRES behaves over time.

4.1.2 Wavelength solution

To find and determine the wavelength solution of HIRES with sufficient accuracy and high precision the astrocomb with the single λ lasers will be used. To increase the accuracy beyond the requirements the wavelength solution of the FTS will be transferred to HIRES. In a second step the FP will be illuminated with the respective ICS. This calibration source will then be fed to the FTS and to HIRES. The FP can be used in reflection and in transmission, providing emission and absorption line profiles to track down the influence of different noise sources. The following steps can be done to get the wavelength solution:

1. Stabilize astrocomb
    Warm-up of electronics, optics, mechanics
    Lock $f_{rep}\&f_{CEO}$
    Measure spectrum with FTS
    Identify subset of modes
    correct if needed (relock to new subset)
    spectral flattening
    adjust intensity
    Measure spectrum of astrocomb and single λ lasers with FTS
    Identify mode numbers close to the single λ lasers
2. Guide the astrocomb and single λ lasers to FE I / FE II / fixed calibration
3. Measure the spectrum with the HIRES spectrographs
4. Identify single λ lasers and the closest mode of the astrocomb
5. Calculate the spectrum with $f_{rep}\&f_{CEO}$ and the mode number incident on each spectrograph
6. Calibrate each order and each pixel
7. Illuminate the FP with their respective ICS
8. Adjust intensity according to requirements
9. Guide the transmitted and reflected light of the FP to FE I / FE II / fixed calibration
10. Redo step 3 - 9 with shuttering selected fibers to obtain the wavelength solution for each fiber

Step 10 is only necessary if each fiber must be calibrated. For high throughput modes (OM1-OM4) this may not be necessary, but for OM5-OM8 this might become feasible.

4.1.3 Simultaneous calibration

By simultaneously observing science light and calibration light the wavelength solution of the offline calibration can be transferred to the science spectrum. This can be done using one of the FE in the OM5-OM8 or / and the fixed calibration. Even though the calibration light and the science objects light ”see“ different FE and fiber bundles the noise generated in the spectrograph and the fibers become comparable. The two FE can also be interchanged from time to time to calibrate each path. With the offline calibration, the wavelength solution of HIRES will be anchored to the FP. To achieve an even higher accuracy and precision the FTS may monitor the behavior of the FP continously, even during simultaneous calibration.

5. SUMMARY

Phase A of an instrument is a phase always witnessing rapid changes in the design until all ideas converge to a technical feasible design which allows to conduct the science cases. On the one hand this is always a time of much discussion and ever changing instruments on the other hand this is the time where new technical solutions can be created, tested and assessed. The rapid success of laser frequency combs in astrophysics can be seen as a strong evidence. The technical challenges to respond to the ever increasing demand for higher accuracy and precision in the astrophysical spectroscopy has lead to the creation of HIRES and consecutively to the design of a calibration unit (CU).

This CU is an instrument on its own. In this publication we outlined which calibration sources are suitable. We briefly described our approach for a single broad-band astrocomb (a more detailled discussion is given in the associated publication by Charsley et. al.[14]) and Fabry-Perots (a more detailled discussion is given in the associated publication by Schäefer et. al.[13]). The Fourier-transform spectrograph (FTS) can be used to create a CU-internal wavelength solution. We showed how this solution can be transferred to the HIRES spectrographs by using the astrocomb and fiducial markers. The FTS can even be used to track down long-term drifts of the instrument and enables to measure the spectral intensity response function of HIRES with high accuracy. We believe that this CU will meet all requirements posed by HIRES' science cases, even enabling the most challenging one.

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