Calibration Unit Design for Keck/High-Resolution Infrared Spectrograph for Exoplanet Characterization (HISPEC)

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ABSTRACT

The latest generation of high-resolution spectrographs on 10m-class telescopes are designed to pursue challenging science cases. Consequently, ever more precise calibration methods are necessary to enable trail-blazing science methodology. We present the High-Resolution Infrared SPectrograph for Exoplanet Characterization (HISPEC) Calibration Unit (CAL), designed to facilitate challenging science cases such as Doppler imaging of exoplanet atmospheres, precision radial velocity, and high-contrast, high-resolution spectroscopy of nearby exoplanets. CAL builds on the heritage of the pathfinder instrument, the Keck Planet Imager and Characterizer (KPIC)[1–3] and utilizes four near-infrared (NIR) light sources encoded with wavelength information that are coupled into single-mode fibers. They can be used synchronously during science observations or asynchronously during daytime calibrations. A uranium hollow cathode lamp (HCL) and a series of gas cells provide absolute calibration from 0.98 μm to 2.46 μm. Two laser frequency combs (LFC) provide stable, time-independent wavelength information during observation, and CAL implements two low-finesse Fabry-Perot etalons as a complement to the LFCs.

Keywords:

1. INTRODUCTION

1.1 HISPEC Design Overview

HISPEC is a high-resolution, diffraction-limited, simultaneous multi-band, fiber-fed spectrograph for W.M. Keck Observatory designed to be an ultra-stable instrument to achieve its science goals. The instrument will operate in the near-infrared (NIR) from 0.98 μm to 2.46 μm and will take spectra in *y*-, *J*-, *H*-, and *K*-band simultaneously. HISPEC will be fed by the Keck adaptive optics (AO) system, with the visible Shack-Hartmann wavefront sensor (SHWFS)[4] working in tandem with a deformable mirror (DM) to supply a diffraction-limited image to HISPEC's input known as front-end instrument (FEI). In 2026/2027, the High-order Advanced Keck Adaptive

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Optics system (HAKA) upgrade[5] will feed HISPEC, bringing better wavefront correction and more consistent instrumental coupling that allow for higher overall throughput during observations. Light from the target is coupled into single-mode optical fiber (SMF) where it is then routed to two spectrographs. The spectrographs, BSPEC (y- and J-band) and RSPEC (H- and K-band), use Teledyne Hawaii H4RG-10μm detectors to take spectra from 0.98 - 1.33 μm and 1.49 - 2.48 μm respectively. The flexibility of and stability of SMF allows for the spectrographs to be located in the basement of the Keck-II telescope, where the instrumentation will benefit from thermal and vibrational isolation. The instrument offers 66 possible configurations, with modes created for simultaneous wavelength calibration and radial velocity stability measurements as well as daytime calibrations, etc. This number of configurations is supported by the use of mechanical fiber switchers that allow for the swapping of inputs to the spectrograph to achieve the desired data product (Jovanovic et al., in prep). This allows HISPEC to be used in many modes during the course of a night of observations, e.g., a precision RV mode where the science target, background, and calibration light are all being taken simultaneously across all detectors.

1.2 CAL Design Overview

A high-fidelity calibration system is necessary to achieve HISPEC's lofty scientific goals. The desired precision for both kinematic and relative flux measurements requires detailed calibration measurements of detector components and simultaneous tracking of drifts in wavelength across the dispersion axis of the detector (in addition to any shifts caused by radial velocity variation) or the line spread function of the instrument. The calibration subsystem (CAL) encompasses all components of HISPEC that result in calibration light reaching the spectrographs. It consists of a set light sources for wavelength calibration, light sources for detector calibration, and the hardware that facilitates their routing to the spectrographs. To add further flexibility, the HISPEC calibration system also uses its own fiber switcher, allowing for all necessary configurations during daytime calibrations and reference calibration during science observations. HISPEC is a completely SMF-fed instrument behind adaptive optics, and the calibration subsystem must conform to this design, maintaining the thermal integrity of the cryostats by delivering calibration light to the through SMF. We have multiple extended sources that are coupled into SMF, producing generally $\sim$10's of nW of integrated power, and piped to the instrument for both wavelength and detector calibration on a defined temporal baseline as well as on demand.

To calibrate the spectrograph across its dispersion axis, we have designed a suite of calibration sources that will act in tandem to derive, characterize, and monitor the wavelength solution of both HISPEC spectrographs. We will use two laser frequency combs (LFC)s as the workhorse wavelength calibrators for BSPEC and RSPEC. BSPEC will receive light from the LFC installed for Keck Planet Finder (KPF).[6,7] KPF is an optical precision radial velocity instrument installed on Keck-I, equipped with an LFC provided by Menlo Systems similar to that of the ESO/HARPS instrument.[8] The LFC is used to calibrate the instrument but generates excess light in the near-infrared (NIR) that nominally goes to waste. We are able to pick-off the excess infrared light and couple it into single mode fiber, where it is then routed through the Keck basement to Keck-II where we connect it to our HISPEC Calibration optical fiber switchyard. A second LFC, the so-called "HK-comb", generates light in the wavelength range of RSPEC.[9]

We will also use two "astro-etalons" to cross-calibrate the spectrograph. These etalons are low-finesse optical cavities with a transmission function that looks similar to the LFCs at the instrumental resolution of HISPEC. The etalons are manufactured by Stable Laser Systems (Boulder, CO) and are identical in specification except for the optical fiber used for the input and output of the etalon, which will mirror the specified optical fiber used for the rest of the fiber runs for BSPEC and RSPEC (Jovanovic et al., in prep). Though the etalons are expected to drift in absolute wavelength space over weeks/months, the drifts will be characterized and the etalons will be able to provide stable wavelength calibration over the course of a night-long observation.

Finally, we employ temperature stabilized gas cells and a uranium hollow cathode lamp to provide wavelength information in RSPEC and BSPEC, respectively. As these sources rely on radiation from electronic transition, under a temperature and pressure controlled system, the wavelength information will not drift over time and will provide wavelength data in an absolute sense, i.e. the data can be compared to transition atlases in the literature. Because HISPEC covers such a large wavelength range at high resolution, we require both NIR-absorbing gases that cover the entire wavelength range in RSPEC and emission lamps that provide lines across the BSPEC bandpass.

In this paper, we describe the technical specifications and details of the HISPEC CAL subsystem design broken down by calibration method and requirement. In Section 2.1, we describe our approach to characterizing the Teledyne Hawaii-4RG10μm detectors for science observations. In Section 2.2, we discuss our suite of wavelength calibration sources and their uses. Finally, Section 3 discusses future measurements to be made by the HISPEC team.

2. CALIBRATION METHODS

2.1 Detector Calibration

2.1.1 Dark Frames

Dark frames are achieved by terminating all input fibers of the spectrograph with Narcissus mirrors. Any thermal radiation coupled into single mode fiber (however little) will be reflected by a gold coating on the tip of a capped fiber. These Narcissus mirrors are integrated into the design in the CAL fiber switch system.

2.1.2 Flat Frames

Understanding the pixel-to-pixel properties and variations across a Teledyne Hawaii H4RG detector is critical to getting to <1 m/s RV precision and as such the capability to flatfield the detectors often and repeatably is required. A good flatfield requires a flat distribution of photon flux across the detector to accurately measure variations in the detector pixels themselves. To this end, CAL provides the ability to flatfield leveraging the SMF design of HISPEC in a variety of scenarios, including controlling the flux density and spectral range projected on each detector. This is accomplished while maintaining the thermal integrity of the cryostat system by removing the light sources from the cryogenic environment, where their heat would dissipate into the environment and disturb the thermal stability of the instrument.

The flatfielding system is divided into two: one unit to flatfield each detector. These solutions are identical in form but optimized for the respective wavelength ranges of BSPEC and RSPEC. Broadband infrared light is generated inside the CAL rack mounted box by a Newport 6363 IR lamp. This component was chosen due to its off-the-shelf availability, cost, and serviceability in addition to the adequate incident power produced by the source.

Originally, a Thorlabs 202L NIR tungsten-halogen lamp was tested, though during a trade study using Palomar Radial Velocity Instrument (PARVI)[10],[11] we saw evidence of high-frequency fringing in the spectrum, which was attributed to transmissive collimating optics in the lamp. While this is not an issue for full-detector flatfields, for the purposes of taking fiber flats and deblazing the spectrograph, this behavior is less than ideal. Moving to the Newport lamp with only reflective optics appeared to remedy this behavior in a similar setup tested with PARVI. In testing, this lamp was shown to have a near-blackbody spectral energy distribution (SED) of ∼1000 K. In addition, we observed far fewer absorption features in the spectra of the Newport lamp which can be attributed to its use of a graphite rod which glows with a classical blackbody peak in the NIR at 1000K as opposed to the tungsten-halogen filament which showed evidence of absorption by the fill gas or contaminates.

While in free space, the light passes through a six-position filter wheel containing one of four bandpass filters and two open positions. The selected filters are shown in Table 1 (BSPEC) and Table 2 (RSPEC).

Vendor	PN	Center Wavelength (nm)	FWHM Bandpass (nm)	Transmittance
Edmund Optics	#87-811	1000	25	>90%
Edmund Optics	#87-813	1100	25	>90%
Edmund Optics	#87-815	1200	25	>90%
Edmund Optics	#87-817	1300	25	>90%

Table 1. HISPEC CAL Filter Wheel Filter Selection BSPEC

Vendor	PN	Center Wavelength (nm)	FWHM Bandpass (nm)	Transmittance
Edmund Optics	#87-821	1500	25	>90%
Edmund Optics	#87-859	1600	50	>90%
Thorlabs	FB1900-200	1900	200 ± 40	>85%
Thorlabs	FB2300-50	2300	50	>70%

Table 2. HISPEC CAL flatfield Filter Wheel Filter Selection RSPEC

Using bandpass filters affords the ability to measure the wavelength-dependent intra-pixel spectral response of the Teledyne Hawaii H4RG-10 detectors while maintaining the classic near-blackbody graphite lamp SED of the Newport 6363 when the filter wheel is in the open position. An image of the CAL Blue channel box that highlights the flatfielding system is shown in Figure 1, and the hardware and optical path are identical for the Red channel. Pseudo-collimated light exits the Newport 6363 IR lamp where it is directed through a six-position filter wheel. In the open position, all the light passes through to the motorized iris diaphragm, which allows for an achromatic attenuation of the light before being focused and injected into a single mode fiber on an XY-translation stage. Because the beam waist of the focused light is greater than the diameter of the single-mode fiber core and the source itself is extended, the XY-translation adjustment is the only necessary adjustment. In the case where a spectral filter is inserted, the selected bandpass will be dispersed on the detector where that bandpass can be better characterized. These boxes will be rack-mounted in the basement of Keck-II.

After being routed to the main body of the spectrograph, the light in the fiber is passed through the vacuum feedthrough specific to flatfielding. Once inside the spectrograph, the fiber is connected to an integrating sphere supplied by Labsphere. We have selected the 3-port, 3-inch diameter Infragold-coated sphere for two reasons. First, this sphere has already been implemented in the PARVI to flatfield their Teledyne Hawaii H2RG detector at cryogenic temperature without issue and has been validated at similar wavelength ranges for use in a cryogenic environment. Second, the Infragold coating provides $\sim 96\%$ Lambertian reflectance in the NIR across our entire wavelength range, meaning that the flatfield will maintain the SED of the light source. At the output window of the integrating sphere, diffused light will travel a minimum of 13.3 cm to the surface of the detector. This distance will ensure a variation of $< 2\%$ in the intensity of light across the detector according to Labsphere. The notional light path of the flatfield inside the cryostat is shown in Figure 2.

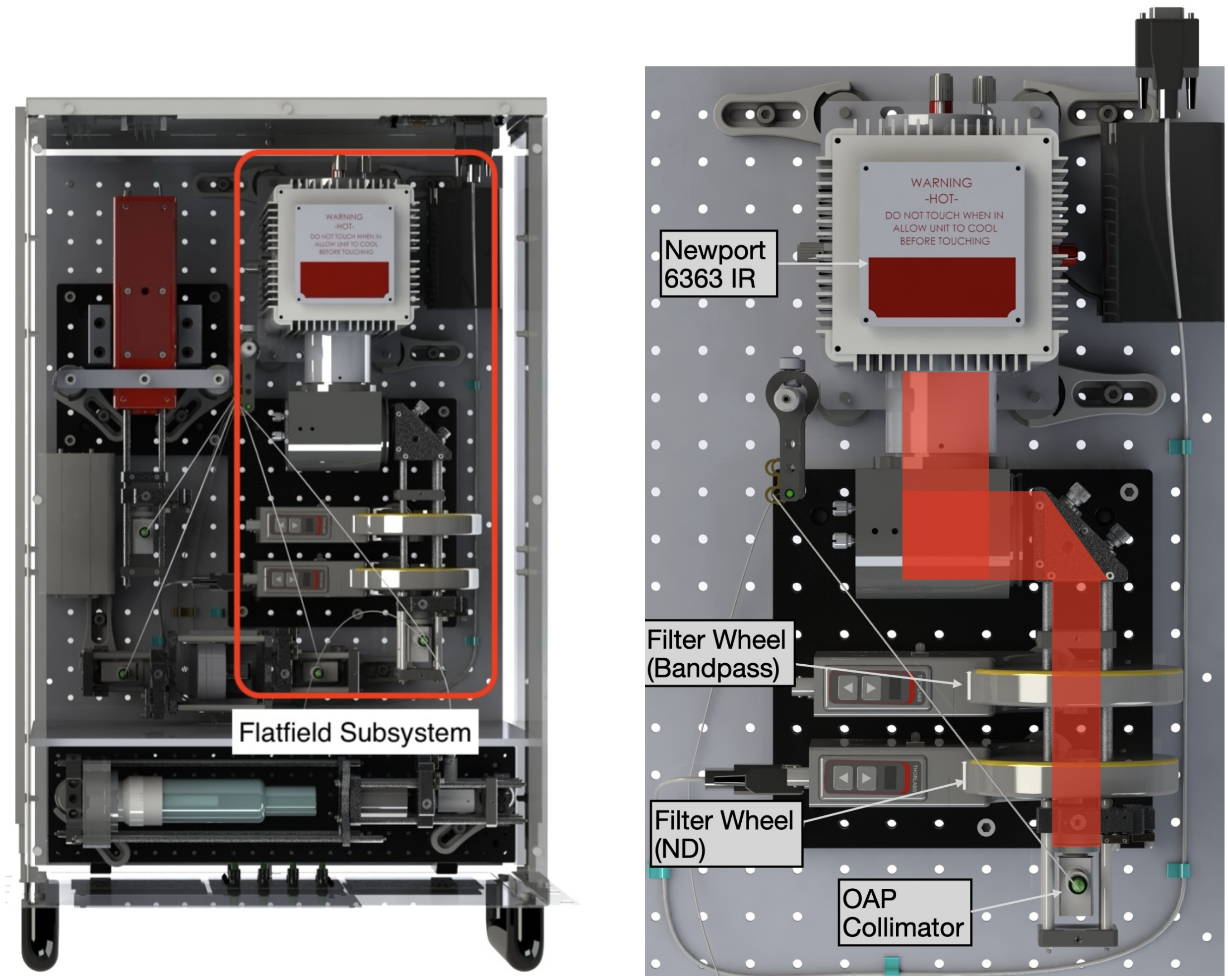
2.1.3 Fiber Flat Frames

The flexibility of the HISPEC fiber switcher means that flatfielding calibration light can also be fed through the science path of the spectrograph. Instead of being fed to the flatfielding port of the spectrograph, the flatfielding port is terminated by a Narcissus mirror and the calibration light is routed to science ports 1, 2, and 3. This configuration allows for the measurement of intra-pixel response of all pixels that will be illuminated with science or calibration light during observations, as well as for trace-finding and determining the optimal placement of the fiber tracers on the detector, attempting to avoid bad pixels, for instance.

2.2 Wavelength Calibration

2.2.1 Laser Frequency Combs

An astrocomb is a Laser Frequency Comb (LFC) calibration source for astronomical spectrographs. Like gas cells, arc lamps, and etalons, it provides light at well-defined frequencies to serve as a "spectral ruler" to compare against target object spectral signatures. Unlike these above sources, a LFC provides wavelength information at standard wavelength intervals in an extremely precise and predictable way. Each "tooth" of the comb is unresolved at the resolution of the spectrograph, which means that the LFC appears as the point spread function of the instrument. As such, it is an important tool for performing precision radial velocity studies of exoplanet-hosting stars. Most LFCs for purposes other than astronomy generally have repetition rates, or how close each comb tooth is to the next, of 100 MHz to 1 GHz. The repetition rate, f_{rep}, controls the offset in wavelength of each PSF in integer numbers. For instance, two comb teeth separated by 20 other teeth have a frequency difference of $\Delta f = (20 + 1)f_{rep}$. A nominal frequency comb repetition rate could be 100 MHz. However at this RF value, the frequency comb would be unresolved at the resolution of HISPEC. In the past, LFCs used for astronomy have employed optical cavities to further filter the comb teeth that are dispersed on the spectrograph.



(a) (b)

Figure 1. (a) HISPEC BSPEC CAL Box with flatfielding Unit Highlighted. (b) The optical path of the flatfielding lamp into SMF. Light emitted from the 6363 IR lamp, an extended source, is collimated by reflective optics internal to the lamp. The light then passes through two filter wheels, one containing bandpass filter and the other containing neutral density filters. the light is then collimated using an off-the-shelf off axis parabola collimator.

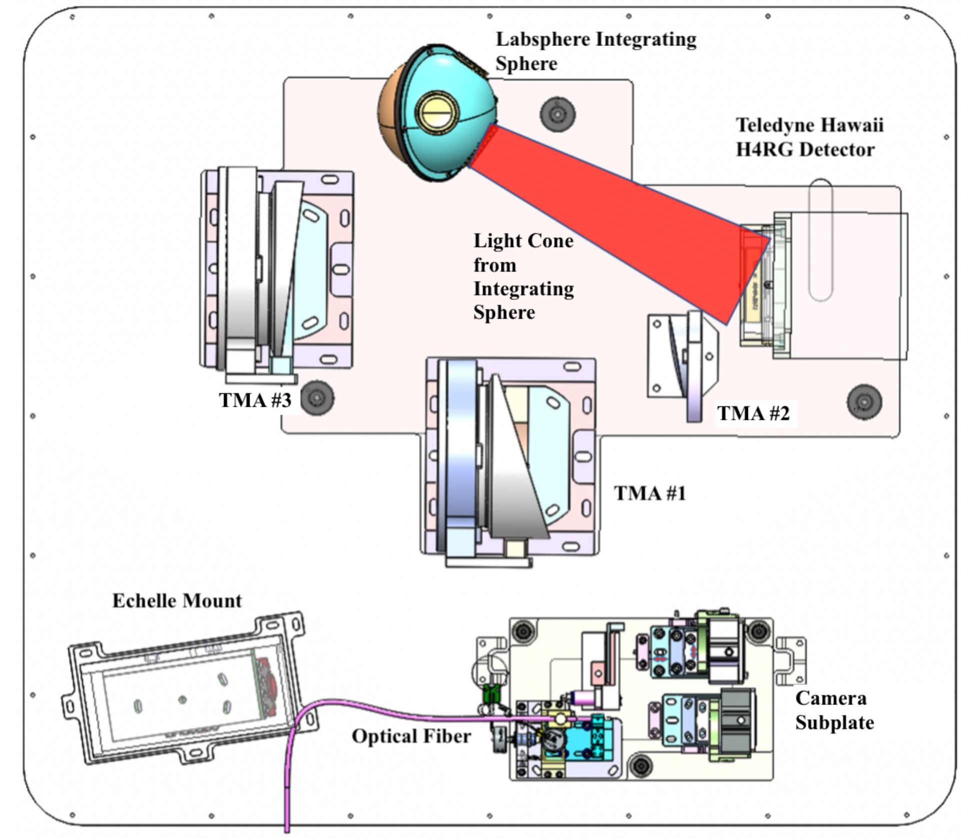


Figure 2. Top-Down view of the HISPEC RSPEC Spectrograph including the integrating sphere and flatfielding light path

This allows individual comb teeth to be resolved by a high resolution spectrograph, even with a slower repetition rate. An astrocomb on the other hand, has a repetition rate near 20 GHz, which is technically challenging to both generate as well as broaden to fit the wavelength range of HISPEC. This process relies on highly non-linear optical materials to create the broad comb spectra needed to cover the full bandpass of the spectrographs, and GPS-disciplined clocks to serve as the astrocomb frequency reference to assure long-term frequency stability of the comb lines. Unlike etalons, the spacing between the lines is traceable to the GPS-disciplined clock signal, meaning both the relative and absolute positions of the light markers are highly stable. Astrocombs are therefore the highest precision and accuracy calibration sources available to astronomical spectrographs. They are also the most complex of these instruments.

There will be two LFC sources available to the HISPEC spectrograph; each generates calibration lines by a different method. The first of these is a commercially available astrocomb manufactured by Menlo Systems and supplied to the W.M. Keck Observatory for the Keck Planet Finder (KPF) instrument.[12] This comb uses spectrally flattened "excess" infrared light produced from the KPF comb. It provides a comb spectrum with a 20 GHz line spacing from 0.970 μm through 1.450 μm with frequency stability performance of <10 cm/s. Menlo combs are mode-locked laser combs that are spectrally filtered through a series of Fabry-Perot filter cavities to achieve a spectrum sparse enough to be resolved on an astronomical spectrograph. KPF uses the optical part of this spectrum with its own spectral flattener for their own science observations, but NIR light is also generated by this comb. That NIR light is picked-off, flattened by a separate spectral flattener, and routed to HISPEC for wavelength calibration in the BSPEC, y-, J-bandpass.

The second comb is an electro-optic (EO) LFC that generates calibration lines by creating sidebands on a continuous-wave (CW) laser through electro-optic modulation at a prescribed RF frequency using EO-phase modulators. The comb is then generated at that RF frequency using an EO-intensity modulator. The result is a "minicomb" of spectral bandwidth and number of lines governed by the RF frequency and the number of cascaded phase modulators. The minicomb must then be spectrally broadened to provide coverage over the desired spectrograph bandpass, and spectrally flattened to provide uniform line intensity. The frequencies of the pump laser and RF oscillator are locked to stable reference signals to provide the overall comb stability needed for spectrograph calibration. The mode spacing of the *H-, K-* EO astrocomb is 16 GHz, and it provides a comb spectrum from 1.500 μm to >2.200 μm. The EO-comb is similar in design to the LFC at the Hobby Eberly Telescope's Habitable Planet Finder[13],[14] Palomar's Radial Velocity Instrument (PARVI)[15],[11] and the Infrared Doppler Instrument on the Subaru Telescope.[16] The *H-, K-* astrocomb was delivered to the W.M. Keck Observatory in the summer of 2023 and is being commissioned using the NIRSPEC spectrograph[17] for initial testing and validation.

2.2.2 Astro-Etalons

A set of etalons will be developed to use in tandem with the other calibration sources. This will shield against unexpected downtime and potentially limited lifetime issues with LFCs. An etalon is a resonant cavity that imprints a comb-like spectral response when broadband light is transmitted through it. Etalons can be independently referenced to other ultra-stable sources but are not for HISPEC by default for simplicity. They are typically run at low pressure (sub-mTorr) and are thermally stabilized to < 1 mK at the zero expansion temperature of the ultra-low expansion (ULE) material used in the cavity and mirrors ($\sim 30°$C in most cases).

PARVI uses a similar astro-etalon to the ones specified for HISPEC. The stability of the PARVI astro-etalon unit was characterized in the laboratory over a time period of days. Built by Stable Laser Systems (Boulder, Colorado), they characterized the etalon with a frequency-stabilized laser by scanning the laser over an etalon resonance line and determining the corresponding central wavelength. That central wavelength was then measured over the course of days to determine the drift of the etalon line. The measured drift of the resonance was 17 kHz/day, which corresponds to a radial velocity shift of about 1.7 cm/s/day at 1 μm, which is acceptable to HISPEC. The drift in frequency is believed to be associated with the ULE relaxing. The ULE will shrink over the course of the first year after it is fabricated at which point the drifts slow. Due to the transparency range of the ULE glass as well as other technical challenges inherent to etalon bandpass, we have elected to use two etalons, one for the y- and J-bands, and the other for the H- and K-bands.

Other PRV instruments like NEID[18] and HPF[13] have used super-continuum sources to illuminate astro-etalons. The benefit of these sources is that they are SMF-coupled and have a broad spectrum, both of which agree with the design philosophy of HISPEC. However, using these lamps carries certain drawbacks; the super-continuum source generates on the order of watts of power and they use a highly reflective cavity for the supercontinuum generation will take weeks to settle after the light source is fed into the cavity due to the thermal load imparted on the cavity. For the calibration to be useful, therefore, the sources would be turned on full-time to allow the cavity to stabilize. Given the repair cadence and cost of supercontinuum sources, a less costly approach is necessary. Furthermore, after generating several watts of power from the supercontinuum source, the light must then be attenuated achromatically to nanowatts of power to reach flux levels appropriate to be incorporated into science observations with the Hawaii H4RG detector. These pressures led HISPEC to adopt a different option: two extended light sources from Thorlabs, the SLS 201L and SLS 203F.

The Thorlabs SLS201L is the source of choice for BSPEC as it comes with a condenser lens and an FC/PC optical fiber adapter. We originally specified and tested the Thorlabs 202L for both RSPEC and BSPEC, but this NIR tungsten-halogen lamp has been discontinued as of March 2024. The SLS201L moves the blackbody peak flux from ∼1500 nm to ∼900 nm, which benefits BSPEC. We therefore have to move to the SLS 203F for RSPEC with a peak flux at 1800 nm. The SLS 203F also uses a "Globar" filament made of silicon carbide as opposed to to a tungsten filament which creates a better, blackbody-like spectrum with fewer absorption features. We have verified that 300 nW of integrated power can be coupled into an SMF from such a lamp, which will need to be attenuated before it can be routed to the spectrograph, even after being spectrally dispersed at $\mathrm{R} = 100,000$. The lamps are predictable, space-efficient, and inexpensive to service over the lifetime of the instrument.

The light sources will be hosted in the same box as the flatfield lamps and gas cells/hollow cathode lamps. The system will consist of the lamp, an iris, and an FC/APC optical fiber adapter as shown in Figure 3. The beam from the lamp is focused and an SMF collects the light at the focus. Given the source is extended, and there is an abundance of flux, the fiber does not need to be aligned precisely with the beam. The large beam waist also

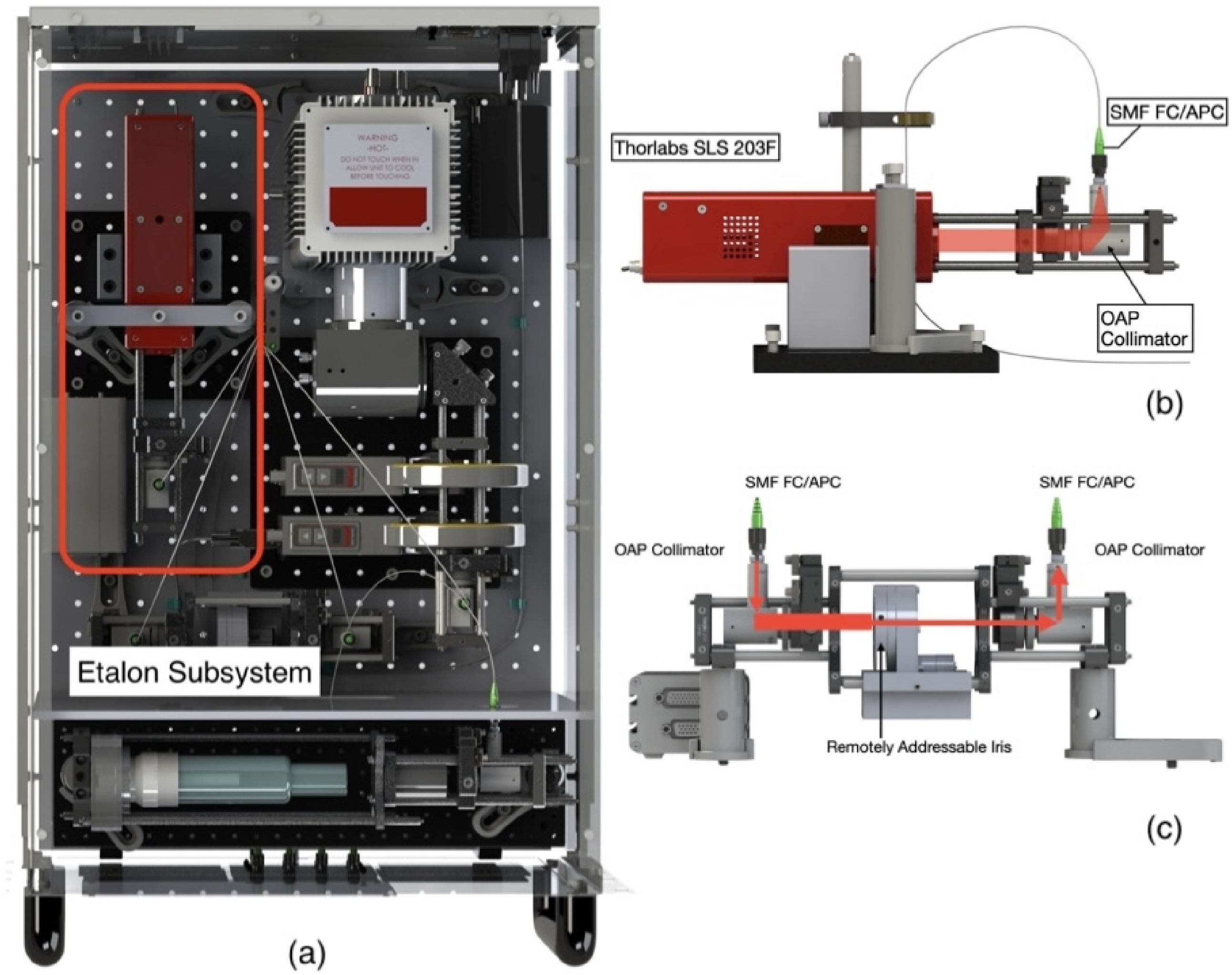


Figure 3. (a) A top down view of the Blue Calibration rack-mounted box with the etalon subsystem highlighted. The subsystem will also include an attenuating iris, which is located beneath a mezzanine with the light source and injection mechanism. (b) A side view of the Thorlabs SLS 203F, meant for the Red Calibration etalon subsystem. Light exits the lamp from a condensing lens and is injected into SMF using a fiber-coupled off-axis parabolic collimator. (c) A side-view of the etalon attenuator, where the light is attenuated achromatically in free space before being re-coupled into SMF and routed to the spectrograph.

makes the fiber alignment highly tolerant and coupled flux is extremely stable over time. A manually adjustable iris will be in the beam before the fiber. The iris will be used to attenuate the light before it goes to the etalon to minimize unnecessary flux being injected into the cavity. The etalon itself is SMF-coupled in and out. After passing through the etalon, which exists in the HISPEC Calibration rack alongside the Blue and Red rackmount boxes, the frequency filtered light returns to the CAL boxes for further attenuation to reach acceptable flux for the spectrographs. This attenuation is accomplished achromatically using a remotely-adjustable iris. The light path of the etalon source and attenuation mechanism is shown in Figure 3.

2.2.3 Gas Cells

Understanding the calibration of the wavelength of the spectrograph and how it changes over time is another key aspect that needs to be carefully calibrated. To enable this, CAL will provide several light sources. The

Cell Name	Gases	Pressure (Torr)	Cell Length (cm)	For Channel
R1	N_2O	228	18.5	Red
R2	CO_2	76	18.5	Red
R3	NH_3	76	18.5	Red
R4	CH_4, H_2O	76, 20	18.5	Red

Table 3. Absolute Wavelength Calibration Species Selection for RSPEC

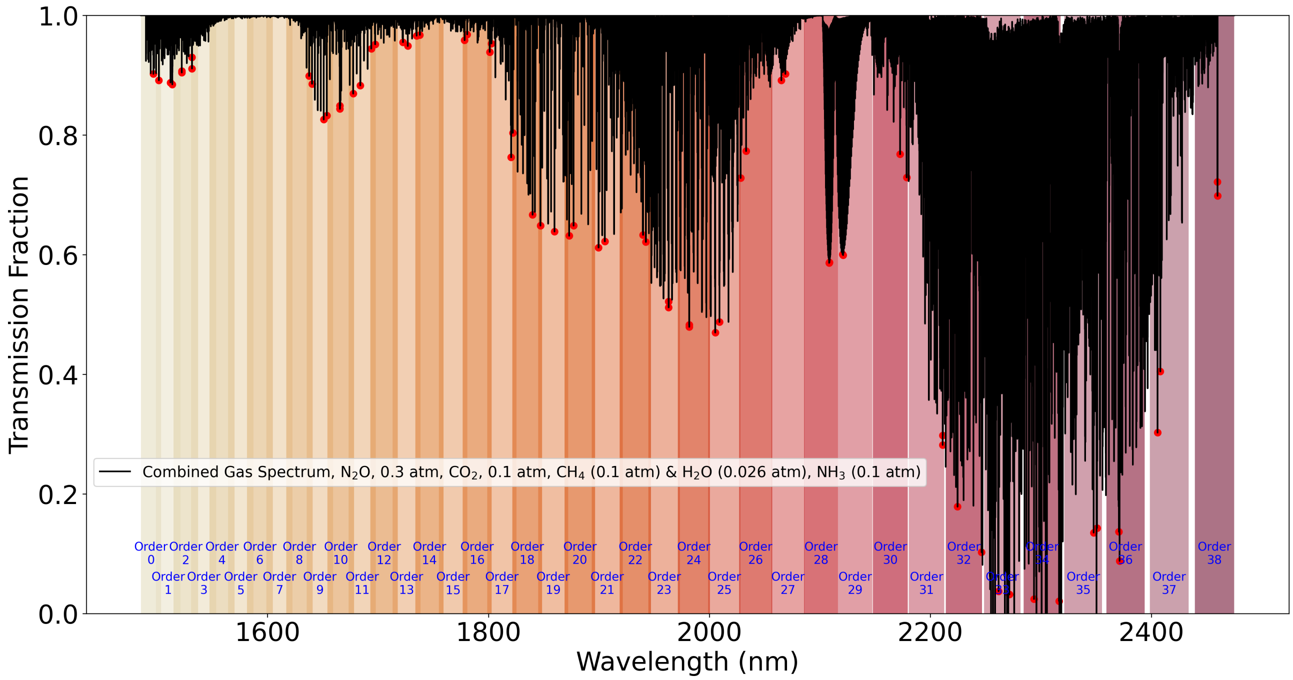
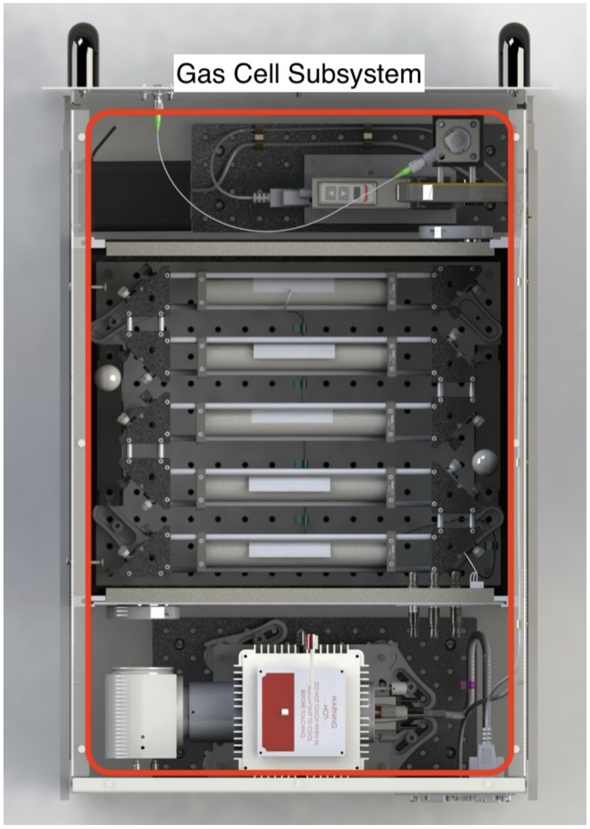


Figure 4. HISPEC CAL Gas Cell Absorption Combined Spectra with absorption line peaks > 10% marked. The gases used are N_2O, NH_3, H_2O, CO_2, and CH_4

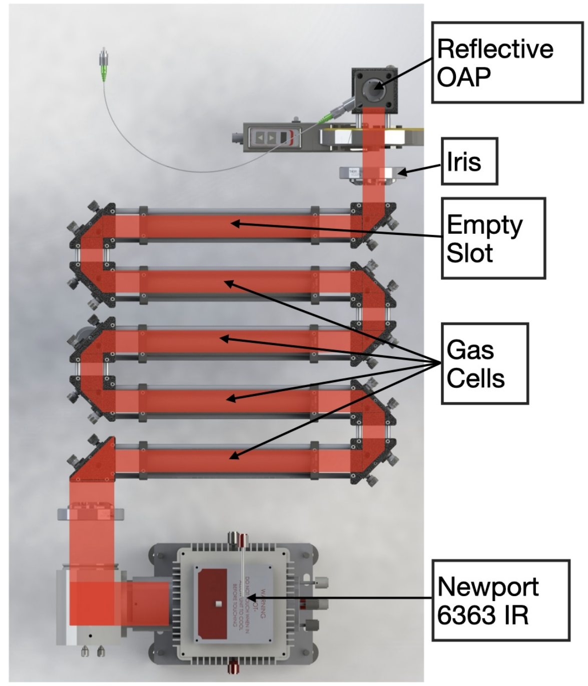
simplest of these are gas cells (GAS) and arc lamps (LMP). These are summarized in Table 3. Four optimized gas cells (with room for an additional cell) for the red spectral channel of HISPEC will be used to offer the most spectral coverage and lines/order for calibration. These gas cells will be illuminated by a Newport 6363 IR lamp for its flat spectral signature, lack of intrinsic absorption features, and reflective collimating optics that are less likely to cause fringing observed by the spectrograph.

Gases were selected by generating predicted spectra using HITRAN Application Program Interface (HAPI)[19] which fetches data from **HITRAN** and uses the spectral information to simulate a gas cell environment where the gases, partial pressures, and cell length are variable. The goal of this exercise was to select a combination of gases that: 1) contained at least two absorption features in each order, 2) contained features that absorbed more than 5% of the incident light to ensure detectable signal above the noise, and 3) had appropriate pressure broadening properties such that the central wavelength of the absorption peak could be measured. The corresponding theoretical spectra of the cells are shown in Figure 4. We focus on optimizing the gas cells for the red spectral channel ($\sim 1.4-2.6\mu$m) as gases that absorb from $0.960-1.320$ μm are not readily available to be manufactured whereas hollow cathode lamps that contain a high density of emission lines in this wavelength range are much more common.

The four gas cells will be produced by Wavelength References, the same company that made gas cells for KPIC. The gas cell entrance windows will be wedged to avoid ghosting and fringing issues inherent in transmissive optics. Though gas cells can be modeled under ideal circumstances, the wavelengths of spectral lines from a given gas cell are not always well understood. This happens because when gas cells are produced, the cells can be contaminated with reactive species, introducing new transitions despite best-practices in manufacturing. We have attempted to minimize reactions by separating each molecule into its own cell, modulo the methane cell



(a)



(b)

Figure 5. The gas cell subsystem is highlighted inside of the CAL red channel box. A Newport 6363 IR lamp is collimated and then directed through 4 gas cells, attenuated via a mechanical addressable iris, and then coupled into SMF before being routed to the spectrograph.

which is combined with water. To limit the presence of unexpected absorption features in our gas cells, we will utilize an R∼200,000 Fourier transform spectrograph at the Jet Propulsion Laboratory to provide a base-truth spectrum of the gas cells. Then, once CAL is integrated and commissioned with the rest of HISPEC, we can use the base truth spectrum to calibrate what data we receive from the instrument. The shifts in the temperature of the gases caused could impact the resulting spectral features as observed on HISPEC. Although simulations have shown that temperature changes in the expected range (i.e., laboratory room temperature to Maunakea summit temperature) have minimal effect on line width at the resolving power of HISPEC, gas cells will be further temperature controlled using polyimide flexible heating adhesive tape. The gas cell system itself will exist inside a secondary layer of thermal insulating material within the Red calibration rack-mounted box. With the line location information provided by JPL, line-matching techniques that are used to calculate the wavelength solution of the instrument become much more reliable and straightforward to implement.

The gas cells will be in the CAL Red Box as shown in Figure 5.

2.2.4 Uranium Hollow Cathode Lamp

Given the lack of common NIR absorbing gases in the BSPEC bandpass (0.98 - 1.327 μm), a different strategy must be used for absolute wavelength calibration. Historically, this has been accomplished by using arc lamps or metal-halide hollow cathode lamps. Thorium/argon lamps are frequently used for PRV instrument calibrations; most recently, they were used to calibrate ESPRESSO at VLT in combination with a Fabry-Perot etalon,[20] though they have also been used to calibrate precision radial velocity instruments like the MAROON-X[21] PRV spectrograph as well as the European Southern Observatory's (ESO) High Accuracy Radial velocity Planet Searcher (HARPS)[22] in the past. However, recently produced thorium hollow cathode lamps have been shown

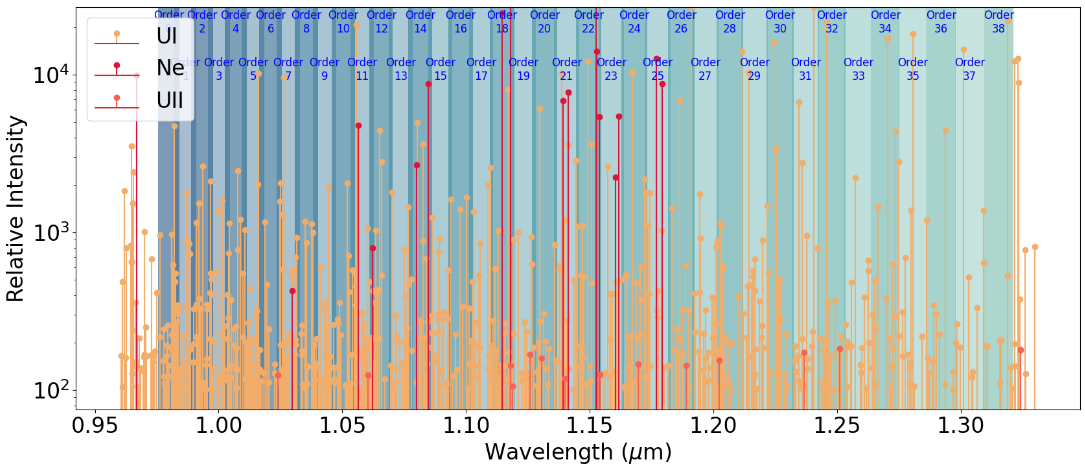


Figure 6. Emission Line Locations of Uranium from a U/Ne hollow cathode lamp, Redman et al. 2012

to be contaminated with thorium oxide (ThO),[23] making it difficult to identify stable thorium emission lines among a forest of moving ThO emission lines. Many recent high-PRV instruments implement a uranium/neon hollow cathode lamp for absolute wavelength calibration, including the Apache Point Observatory Galactic Evolution Experiment (APOGEE) Spectrographs,[24] the CRyogenic high-resolution InfraRed Echelle Spectrograph (CRIRES+),[25] and the Habitable Zone Planet Finder (HPF).[13] In the optical band, U/Ne is an optimal choice for astronomy due to its high information density at this bandpass, though as we explore past 1.2 μm and certainly at 2.460 μm, that information density decreases. We will make use of a uranium/neon hollow cathode lamp that provides complete wavelength information about the blue spectra channel. Using the U/Ne atlas in Redman et al. 2012,[26] the emission line locations along with their relative intensities (given in arbitrary SNR) are determined for both the red and blue channels of HISPEC. The theoretical HCL emission line locations are shown in Figure 6.

The U/Ne lamp light is coupled directly into SMF where it is routed out of the Blue CAL box to the CAL switch at which point it may be routed to BSPEC Calibration fiber when in use. We have measured 80 nW of integrated power from this extended source coupled into SMF, and do not expect any difficulty achieving the necessary SNR for calibration with HISPEC from our testing with the less sensitive PARVI H2RG detectors. The light path of the hollow cathode lamp and its location in the CAL Blue box is shown in Figure 6.

3. FUTURE INVESTIGATIONS

HISPEC is entering its manufacturing phase, with CAL slated to be the first completed system. Once the CAL Blue and CAL Red rack-mounted boxes are completed, testing using PARVI will provide helpful, real-world data on their calibration precision capabilities as well as signal intensities. We plan on measuring both our gas cells and hollow cathode lamp with PARVI, matching the gas cell data to both the HITRAN line lists and characterization spectra taken with the JPL FTS. These comparisons will greatly aid the development of a wavelength solution during the commissioning of HISPEC. Similarly, the Redman et al. Uranium atlas[26] coupled with data taken by SPIRou's hollow cathode lamp[27] will provide the comparison to our hollow cathode lamp system.

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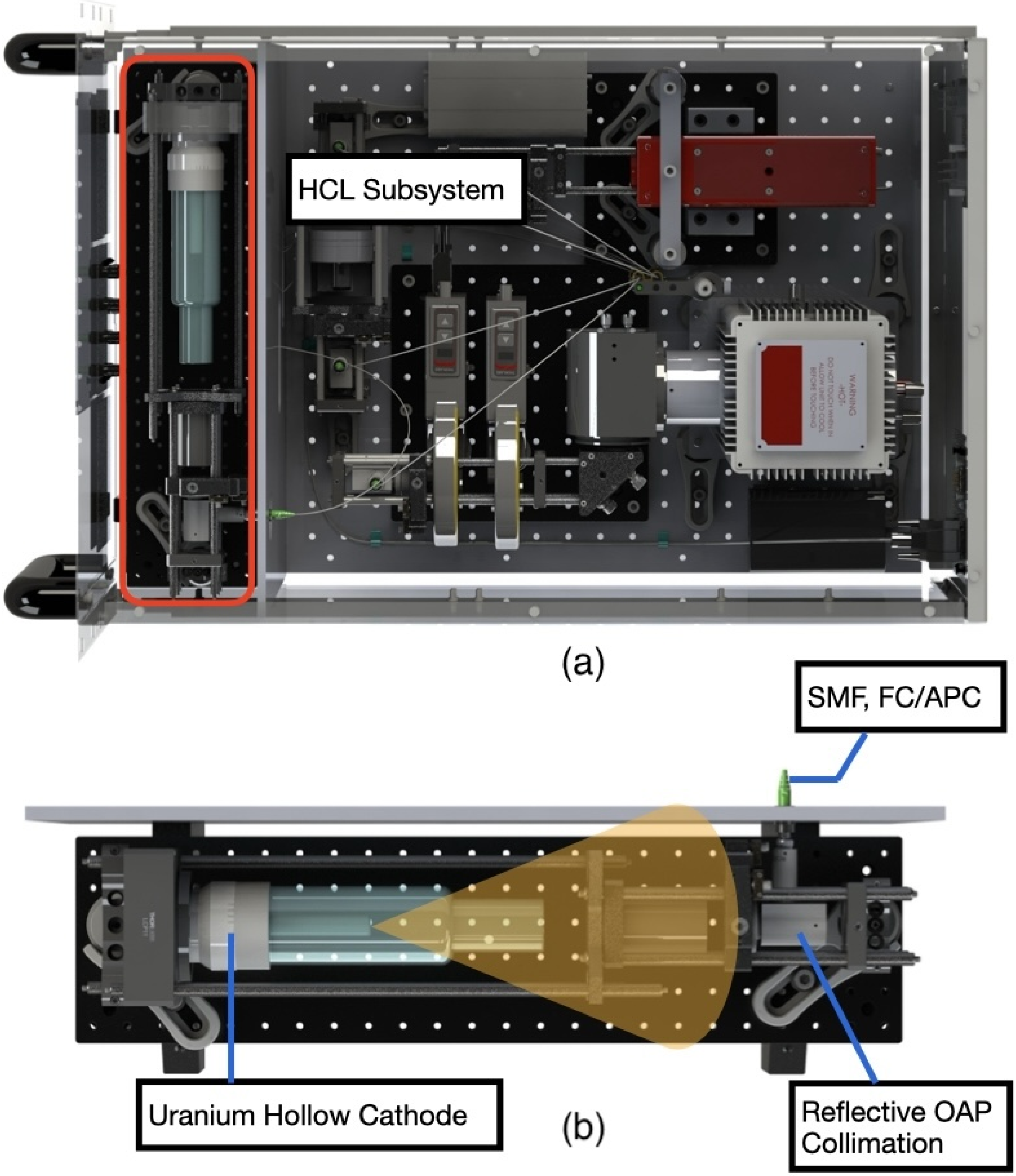

Figure 7. (a) A top down view of the Blue rack-mounted CAL box with the hollow cathode lamp subsystem highlighted. The HCL is shielded from the other subsystems in this box to limit exposure to UV light. (b) The U/Ne HCL is an extended light source. We use an OAP collimator to couple its light into SMF.

REFERENCES

[1] Mawet, D., Wizinowich, P., Dekany, R., Chun, M., Hall, D., Cetre, S., Guyon, O., Wallace, J. K., Bowler, B., Liu, M., Ruane, G., Serabyn, E., Bartos, R., Wang, J., Vasisht, G., Fitzgerald, M., Skemer, A., Ireland, M., Fucik, J., Fortney, J., Crossfield, I., Hu, R., and Benneke, B., "Keck Planet Imager and Characterizer: Concept and phased implementation," in [*Adaptive Optics Systems V*], **9909**, 143–149, SPIE (July 2016).

[2] Delorme, J.-R., Jovanovic, N., Echeverri, D., Mawet, D. P., Wallace, J. K., Bartos, R. D., Cetre, S., Wizinowich, P. L., Ragland, S., Lilley, S. J., Wetherell, E., Doppmann, G., Wang, J. J., Morris, E. C., Ruffio, J.-B., Martin, E. C., Fitzgerald, M. P., Ruane, G. J., Schofield, T., Suominen, N., Calvin, B., Wang, E., Magnone, K. G., Johnson, C. A., Sohn, J. M., Lopez, R. A., Bond, C. Z., Pezzato, J., Llop-Sayson, J., Chun, M. R., and Skemer, A. J., "Keck Planet Imager and Characterizer: A dedicated single-mode fiber injection unit for high-resolution exoplanet spectroscopy," *Journal of Astronomical Telescopes, Instruments, and Systems* **7**, 035006 (Aug. 2021).

[3] Delorme, J. R., Jovanovic, N., Wallace, J. K., Bartos, R. D., Echeverri, D., Bond, C. Z., Cetre, S., Lilley, S., Jacobson, S., Mawet, D., Wizinowich, P. L., and Fitzgerald, M., "First version of the fiber injection unit for the Keck Planet Imager and Characterizer," in [*Ground-Based and Airborne Instrumentation for Astronomy VII*], **10702**, 668–675, SPIE (July 2018).

[4] Wizinowich, P., Acton, D. S., Shelton, C., Stomski, P., Gathright, J., Ho, K., Lupton, W., Tsubota, K., Lai, O., Max, C., Brase, J., An, J., Avicola, K., Olivier, S., Gavel, D., Macintosh, B., Ghez, A., and Larkin, J., "First light adaptive optics images from the keck ii telescope: A new era of high angular resolution imagery," *Publications of the Astronomical Society of the Pacific* **112**, 315 (3 2000).

[5] Wizinowich, P., Cetre, S., Chin, J., Correia, C., Gers, L., Guthery, C., Karkar, S., Kwok, S. H., Lilley, S., Lyke, J., and et. al., "Keck adaptive optics current and future roles as an elt pathfinder," in [*Adaptive Optics for Extremely Large Telescopes 7th Edition*], ONERA, Avignon, France (June 2023).

[6] Wu, Y., Huang, Z., Steinmetz, T., Yeo, M., Stockwald, K., and Holzwarth, R., "20 GHz astronomical laser frequency comb with super-broadband spectral coverage," in [*Ground-based and Airborne Instrumentation for Astronomy IX*], Evans, C. J., Bryant, J. J., and Motohara, K., eds., **12184**, 121841J, International Society for Optics and Photonics, SPIE (2022).

[7] Gibson, S. R., Howard, A. W., Rider, K., Roy, A., Edelstein, J., Kassis, M., Grillo, J., Halverson, S., Sirk, M. M., Smith, C., Allen, S., Baker, A., Beichman, C., Berriman, B., Brown, T., Casey, K., Chin, J., Coutts, D., Cowley, D., Deich, W., Feger, T., Fulton, B., Gers, L., Gurevich, Y., Ishikawa, Y., James, E., Jelinsky, S., Kaye, S., Lanclos, K., Li, A., Lilley, S., McCarney, B., Miller, T., Milner, S., O'Hanlon, T. J., Pember, J., Raffanti, M., Rockosi, C., Rubenzahl, R., Rumph, D., Sandford, D., Savage, M., Schwab, C., Seifahrt, A., Shaum, A., Smith, R., Stuermer, J., Thorne, J., Vandenberg, A., Boeckmann, T. V., Wang, C., Wang, Q., Weisfeiler, M., Wilcox, M., Wishnow, E. H., Wizinowich, P., Wold, T., and Wolfenberger, A., "Keck Planet Finder: design updates," in [*Ground-based and Airborne Instrumentation for Astronomy VIII*], Evans, C. J., Bryant, J. J., and Motohara, K., eds., **11447**, 1144742, International Society for Optics and Photonics, SPIE (2020).

[8] Probst, R. A., Curto, G. L., Avila, G., Martins, B. L. C., de Medeiros, J. R., Esposito, M., Hernández, J. I. G., Hänsch, T. W., Holzwarth, R., Kerber, F., Leão, I. C., Manescau, A., Pasquini, L., Rebolo-López, R., Steinmetz, T., Udem, T., and Wu, Y., "A laser frequency comb featuring sub-cm/s precision for routine operation on HARPS," in [*Ground-based and Airborne Instrumentation for Astronomy V*], Ramsay, S. K., McLean, I. S., and Takami, H., eds., **9147**, 91471C, International Society for Optics and Photonics, SPIE (2014).

[9] Kassis, M., Allen, S. L., Alverez, C., Baker, A., Banyal, R. K., Bertz, R., Beichman, C., Brown, A., Brown, M., Bundy, K., Cabak, G., Cetre, S., Chin, J., Chun, M. R., Cooke, J., Delorme, J., Deich, W., Dekany, R. G., Devenot, M., Doppmann, G., Edelstein, J., Fitzgerald, M. P., Fucik, J. R., Gao, M., Gibson, S., Gillingham, P. R., Gomez, P., Gottschalk, C., Halverson, S., Hill, G., Hinz, P., Holden, B. P., Howard, A. W., Jones, T., Jovanovic, N., Kirby, E., Krishnan, S., Kupke, R., Lanclos, K., Larkin, J. E., Leifer, S. D., Lewis, H. A., Lilley, S., Lu, J. R., Lyke, J. E., MacDonald, N., Martin, C., Mather, J., Matuszewski, M., Mawet, D., McCarney, B., McGurk, R., Marin, E., Millar-Blanchaer, M. A., Nance, C., Nash, R. B., Neill, J. D., O'Meara, J. M., Peretz, E., Poppett, C., Konopacky, Q., Radovan, M. V., Ragland, S., Rider, K., Roberts, M., Rockosi, C., Rubenzahl, R., Sallum, S., Sandford, D., Savage, M., Simha, S., Skemer,

A. J., Steidel, C. C., Stelter, R. D., Surendran, A., Walawender, J., Westfall, K. B., Wizinowich, P., Wright, S., and Yeh, S., "W. m. keck observatory instrumentation status and future direction," *Astronomische Nachrichten* **344**(8-9), e20230088 (2023).

[10] Gibson, R. K., Oppenheimer, R., Nilsson, R., Beichman, C. A., and Vasisht, G., "Data reduction pipeline and performance for the Palomar radial velocity instrument," *Journal of Astronomical Telescopes, Instruments, and Systems* **8**, 038006 (Sept. 2022).

[11] Cale, B. L., Kesseli, A., Beichman, C., Vasisht, G., Gibson, R. K., Oppenheimer, R., Fucik, J., Mawet, D., Paine, C., Matthews, K., Lockhart, T., Halverson, S., Shen, B., Bagheri, M., Leifer, S., Plavchan, P., and Hover, D., "Commissioning observations of HD 189733 with the PAlomar Radial Velocity Instrument," *Journal of Astronomical Telescopes, Instruments, and Systems* **9**, 038006 (July 2023).

[12] Gibson, S. R., Howard, A. W., Roy, A., and Smith, R., [*Keck Planet Finder: preliminary design*], Art. No. 107025X, Society of Photo-optical Instrumentation Engineers (SPIE) (7 2018). Funding by Heising-Simons Foundation.

[13] Mahadevan, S., Ramsey, L., Bender, C., Terrien, R., Wright, J. T., Halverson, S., Hearty, F., Nelson, M., Burton, A., Redman, S., Osterman, S., Diddams, S., Kasting, J., Endl, M., and Deshpande, R., "The habitable-zone planet finder: a stabilized fiber-fed NIR spectrograph for the Hobby-Eberly Telescope," in [*Ground-based and Airborne Instrumentation for Astronomy IV*], McLean, I. S., Ramsay, S. K., and Takami, H., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8446**, 84461S (Sept. 2012).

[14] Metcalf, A. J., Anderson, T., Bender, C. F., Blakeslee, S., Brand, W., Carlson, D. R., Cochran, W. D., Diddams, S. A., Endl, M., Fredrick, C., Halverson, S., Hickstein, D. D., Hearty, F., Jennings, J., Kanodia, S., Kaplan, K. F., Levi, E., Lubar, E., Mahadevan, S., Monson, A., Ninan, J. P., Nitroy, C., Osterman, S., Papp, S. B., Quinlan, F., Ramsey, L., Robertson, P., Roy, A., Schwab, C., Sigurdsson, S., Srinivasan, K., Stefansson, G., Sterner, D. A., Terrien, R., Wolszczan, A., Wright, J. T., and Ycas, G., "Stellar spectroscopy in the near-infrared with a laser frequency comb," *Optica* **6**, 233–239 (2 2019).

[15] Gibson, R. K., Oppenheimer, R., Nilsson, R., Beichman, C., and Vasisht, G., "Data reduction pipeline and performance for the Palomar radial velocity instrument," *Journal of Astronomical Telescopes, Instruments, and Systems* **8**, 038006 (July 2022).

[16] Kotani, T., Tamura, M., Nishikawa, J., Ueda, A., Kuzuhara, M., Omiya, M., Hashimoto, J., Ishizuka, M., Hirano, T., Suto, H., Kurokawa, T., Kokubo, T., Mori, T., Tanaka, Y., Kashiwagi, K., Konishi, M., Kudo, T., Sato, B., Jacobson, S., Hodapp, K. W., Hall, D. B., Aoki, W., Usuda, T., Nishiyama, S., Nakajima, T., Ikeda, Y., Yamamuro, T., Morino, J.-I., Baba, H., Hosokawa, K., Ishikawa, H., Narita, N., Kokubo, E., Hayano, Y., Izumiura, H., Kambe, E., Kusakabe, N., Kwon, J., Ikoma, M., Hori, Y., Genda, H., Fukui, A., Fujii, Y., Kawahara, H., Olivier, G., Jovanovic, N., Harakawa, H., Hayashi, M., Hidai, M., Machida, M., Matsuo, T., Nagata, T., Ogihara, M., Takami, H., Takato, N., Terada, H., and Oh, D., "The infrared Doppler (IRD) instrument for the Subaru telescope: instrument description and commissioning results," in [*Ground-based and Airborne Instrumentation for Astronomy VII*], Evans, C. J., Simard, L., and Takami, H., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10702**, 1070211 (July 2018).

[17] McLean, I. S., Becklin, E. E., Bendiksen, O., Brims, G., Canfield, J., Figer, D. F., Graham, J. R., Hare, J., Lacayanga, F., Larkin, J. E., Larson, S. B., Levenson, N., Magnone, N., Teplitz, H., and Wong, W., "Design and development of NIRSPEC: a near-infrared echelle spectrograph for the Keck II telescope," in [*Infrared Astronomical Instrumentation*], Fowler, A. M., ed., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **3354**, 566–578 (Aug. 1998).

[18] Schwab, C., Rakich, A., Gong, Q., Mahadevan, S., Halverson, S. P., Roy, A., Terrien, R. C., Robertson, P. M., Hearty, F. R., Levi, E. I., Monson, A. J., Wright, J. T., McElwain, M. W., Bender, C. F., Blake, C. H., Stürmer, J., Gurevich, Y. V., Chakraborty, A., and Ramsey, L. W., "Design of NEID, an extreme precision Doppler spectrograph for WIYN," in [*Ground-based and Airborne Instrumentation for Astronomy VI*], Evans, C. J., Simard, L., and Takami, H., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **9908**, 99087H (Aug. 2016).

[19] Kochanov, R. V., Gordon, I. E., Rothman, L. S., Wcisło, P., Hill, C., and Wilzewski, J. S., "HITRAN Application Programming Interface (HAPI): A comprehensive approach to working with spectroscopic data," *Journal of Quantitative Spectroscopy and Radiative Transfer* **177**, 15–30 (July 2016).

[20] Schmidt, T. M., Molaro, P., Murphy, M. T., Lovis, C., Cupani, G., Cristiani, S., Pepe, F. A., Rebolo, R., Santos, N. C., Abreu, M., Adibekyan, V., Alibert, Y., Aliverti, M., Allart, R., Allende Prieto, C., Alves, D., Baldini, V., Broeg, C., Cabral, A., Calderone, G., Cirami, R., Coelho, J., Coretti, I., D'Odorico, V., Di Marcantonio, P., Ehrenreich, D., Figueira, P., Genoni, M., Génova Santos, R., González Hernández, J. I., Kerber, F., Landoni, M., Leite, A. C. O., Lizon, J.-L., Lo Curto, G., Manescau, A., Martins, C. J. A. P., Megévand, D., Mehner, A., Micela, G., Modigliani, A., Monteiro, M., Monteiro, M. J. P. F. G., Mueller, E., Nunes, N. J., Oggioni, L., Oliveira, A., Pariani, G., Pasquini, L., Redaelli, E., Riva, M., Santos, P., Sosnowska, D., Sousa, S. G., Sozzetti, A., Suárez Mascareño, A., Udry, S., Zapatero Osorio, M.-R., and Zerbi, F., "Fundamental physics with ESPRESSO: Towards an accurate wavelength calibration for a precision test of the fine-structure constant," *Astronomy and Astrophysics* **646**, A144 (Feb. 2021).

[21] Seifahrt, A., Stürmer, J., Bean, J. L., and Schwab, C., "MAROON-X: a radial velocity spectrograph for the Gemini Observatory," in [*Ground-based and Airborne Instrumentation for Astronomy VII*], Evans, C. J., Simard, L., and Takami, H., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10702**, 107026D (July 2018).

[22] Cosentino, R., Lovis, C., Pepe, F., Collier Cameron, A., Latham, D. W., Molinari, E., Udry, S., Bezawada, N., Black, M., Born, A., Buchschacher, N., Charbonneau, D., Figueira, P., Fleury, M., Galli, A., Gallie, A., Gao, X., Ghedina, A., Gonzalez, C., Gonzalez, M., Guerra, J., Henry, D., Horne, K., Hughes, I., Kelly, D., Lodi, M., Lunney, D., Maire, C., Mayor, M., Micela, G., Ordway, M. P., Peacock, J., Phillips, D., Piotto, G., Pollacco, D., Queloz, D., Rice, K., Riverol, C., Riverol, L., San Juan, J., Sasselov, D., Segransan, D., Sozzetti, A., Sosnowska, D., Stobie, B., Szentgyorgyi, A., Vick, A., and Weber, L., "Harps-N: the new planet hunter at TNG," in [*Ground-based and Airborne Instrumentation for Astronomy IV*], McLean, I. S., Ramsay, S. K., and Takami, H., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8446**, 84461V (Sept. 2012).

[23] Nave, G., Kerber, F., Den Hartog, E. A., and Lo Curto, G., "The dirt in astronomy's genie lamp: ThO contamination of Th-Ar calibration lamps," in [*Observatory Operations: Strategies, Processes, and Systems VII*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10704**, 1070407 (July 2018).

[24] Wilson, J. C., Hearty, F. R., Skrutskie, M. F., Majewski, S. R., Holtzman, J. A., Eisenstein, D., Gunn, J., Blank, B., Henderson, C., Smee, S., Nelson, M., Nidever, D., Arns, J., Barkhouser, R., Barr, J., Beland, S., Bershady, M. A., Blanton, M. R., Brunner, S., Burton, A., Carey, L., Carr, M., Colque, J. P., Crane, J., Damke, G. J., Davidson, J. W., J., Dean, J., Di Mille, F., Don, K. W., Ebelke, G., Evans, M., Fitzgerald, G., Gillespie, B., Hall, M., Harding, A., Harding, P., Hammond, R., Hancock, D., Harrison, C., Hope, S., Horne, T., Karakla, J., Lam, C., Leger, F., MacDonald, N., Maseman, P., Matsunari, J., Melton, S., Mitcheltree, T., O'Brien, T., O'Connell, R. W., Patten, A., Richardson, W., Rieke, G., Rieke, M., Roman-Lopes, A., Schiavon, R. P., Sobeck, J. S., Stolberg, T., Stoll, R., Tembe, M., Trujillo, J. D., Uomoto, A., Vernieri, M., Walker, E., Weinberg, D. H., Young, E., Anthony-Brumfield, B., Bizyaev, D., Breslauer, B., De Lee, N., Downey, J., Halverson, S., Huehnerhoff, J., Klaene, M., Leon, E., Long, D., Mahadevan, S., Malanushenko, E., Nguyen, D. C., Owen, R., Sánchez-Gallego, J. R., Sayres, C., Shane, N., Shectman, S. A., Shetrone, M., Skinner, D., Stauffer, F., and Zhao, B., "The Apache Point Observatory Galactic Evolution Experiment (APOGEE) Spectrographs," *Publications of the ASP* **131**, 055001 (May 2019).

[25] Seemann, U., Anglada-Escude, G., Baade, D., Bristow, P., Dorn, R. J., Follert, R., Gojak, D., Grunhut, J., Hatzes, A. P., Heiter, U., Ives, D. J., Jeep, P., Jung, Y., Käufl, H. U., Kerber, F., Klein, B., Lizon, J. L., Lockhart, M., Löwinger, T., Marquart, T., Oliva, E., Paufique, J., Piskunov, N., Pozna, E., Reiners, A., Smette, A., Smoker, J., Stempels, E., and Valenti, E., "Wavelength calibration from 1-5μm for the CRIRES+ high-resolution spectrograph at the VLT," in [*Ground-based and Airborne Instrumentation for Astronomy V*], Ramsay, S. K., McLean, I. S., and Takami, H., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **9147**, 91475G (Aug. 2014).

[26] Redman, S. L., Ycas, G. G., Terrien, R., Mahadevan, S., Ramsey, L. W., Bender, C. F., Osterman, S. N., Diddams, S. A., Quinlan, F., Lawler, J. E., and Nave, G., "A High-resolution Atlas of Uranium-Neon in the H Band," **199**, 2 (Mar. 2012).

[27] Hobson, M. J., Bouchy, F., Cook, N. J., Artigau, E., Moutou, C., Boisse, I., Lovis, C., Carmona, A., Delfosse, X., Donati, J. F., and SPIRou Team, "The SPIRou wavelength calibration for precise radial velocities in the near infrared," **648**, A48 (Apr. 2021).