

Wavelength calibration from $1 - 5\mu\text{m}$ for the CRIRES+ high-resolution spectrograph at the VLT

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ABSTRACT

CRIRES at the VLT is one of the few adaptive optics enabled instruments that offer a resolving power of 10^5 from $1 - 5\mu\text{m}$. An instrument upgrade (CRIRES+) is proposed to implement cross-dispersion capabilities, spectro-polarimetry modes, a new detector mosaic, and a new gas absorption cell. CRIRES+ will boost the simultaneous wavelength coverage of the current instrument ($\sim \lambda/70$ in a single-order) by a factor of $\gtrsim 10$ in the cross-dispersed configuration, while still retaining a 10 arcsec slit suitable for long-slit spectroscopy. CRIRES+ dramatically enhances the instrument's observing efficiency, and opens new scientific opportunities. These include high-precision radial-velocity studies on the 3 m/s level to characterize extra-solar planets and their atmospheres, which demand for specialized, highly accurate wavelength calibration techniques. In this paper, we present a newly developed absorption gas-cell to enable high-precision wavelength calibration for CRIRES+. We also discuss the strategies and developments to cover the full operational spectral range ($1 - 5\mu\text{m}$), employing hollow-cathode emission lamps, Fabry-Pérot étalons, and absorption gas-cells.

Keywords: astronomical instrumentation, infrared spectrographs, high spectral resolution, upgrade of existing VLT instruments, infrared spectrometers, wavelength calibration, radial-velocities, extra-solar planets

1. INTRODUCTION

The CRyogenic high-resolution InfraRed Echelle Spectrograph (CRIRES³) is installed on UT1 (Antu) of ESO's Very Large Telescope (VLT), and is in operation since 2006. The spectrograph features a nominal resolving power of $R = 10^5$ (using a $0.2''$ slit) over the entire $1 - 5\mu\text{m}$ near-infrared (NIR) wavelength domain. CRIRES is equipped with a MACAO⁴ adaptive optics module to enhance the energy concentration within the 0.2×30 arcsec slit. A single order is dispersed on a focal plane mosaic of 4 $1\text{k} \times 1\text{k}$ InSb Aladdin detectors,⁵ resulting in a simultaneous wavelength coverage of about $\lambda/70$ (at $1\mu\text{m}$) to $\lambda/50$ (at $5\mu\text{m}$).

The CRIRES upgrade project aims to increase the observing efficiency of the instrument, transforming it into a cross-dispersed echelle spectrograph with new capabilities, termed "CRIRES+". The major changes implemented by the upgrade comprise a cross-dispersion unit in place of the existing prism pre-disperser, a new focal plane array of 3 HAWAII-2RG $2\text{k} \times 2\text{k}$ IR detectors, introduction of a new spectro-polarimeter, and additional means of wavelength calibration to enable high-precision velocimetry using a gas-absorption cell. The

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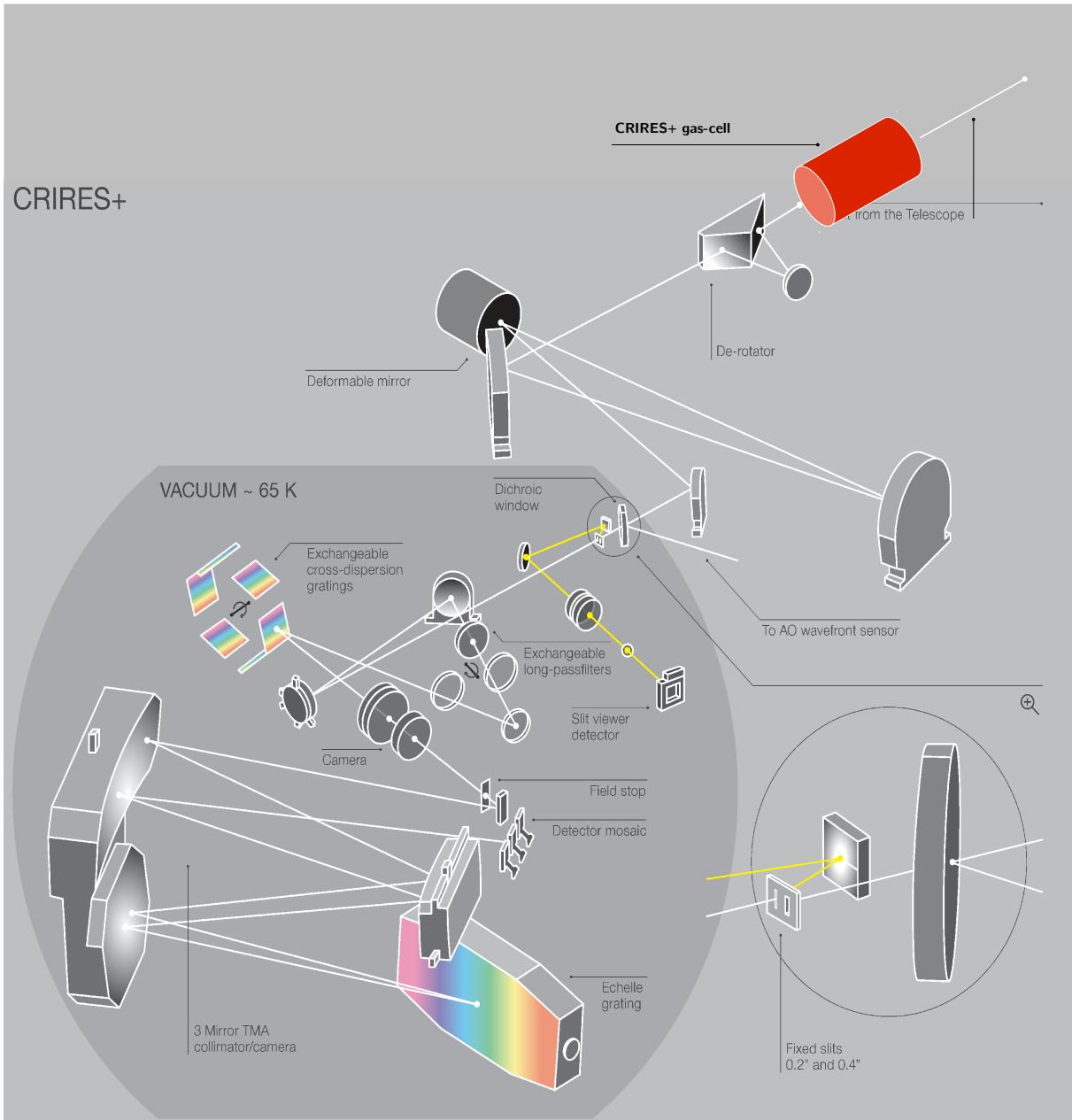


Figure 1. Optical layout of the upgraded CRIRES, termed “CRIRES+”. The instrument itself is located in a cryostat (dark shaded area), interfaced by a dichroic entrance window. The upgraded optics^{1,2} consist of cross-dispersion capabilities (via a grating wheel), camera, and a new 3-chip detector mosaic. The adaptive optics module, the instrument derotator, and calibration devices are comprised in a warm part between the telescope and the spectrograph (light grey area). Wavelength calibration sources are inserted into the optical beam just after the telescope. This is where the new absorption gas-cell is mounted (red cylinder), as well as feeds for emission line lamps, étalons, and a polarimeter.

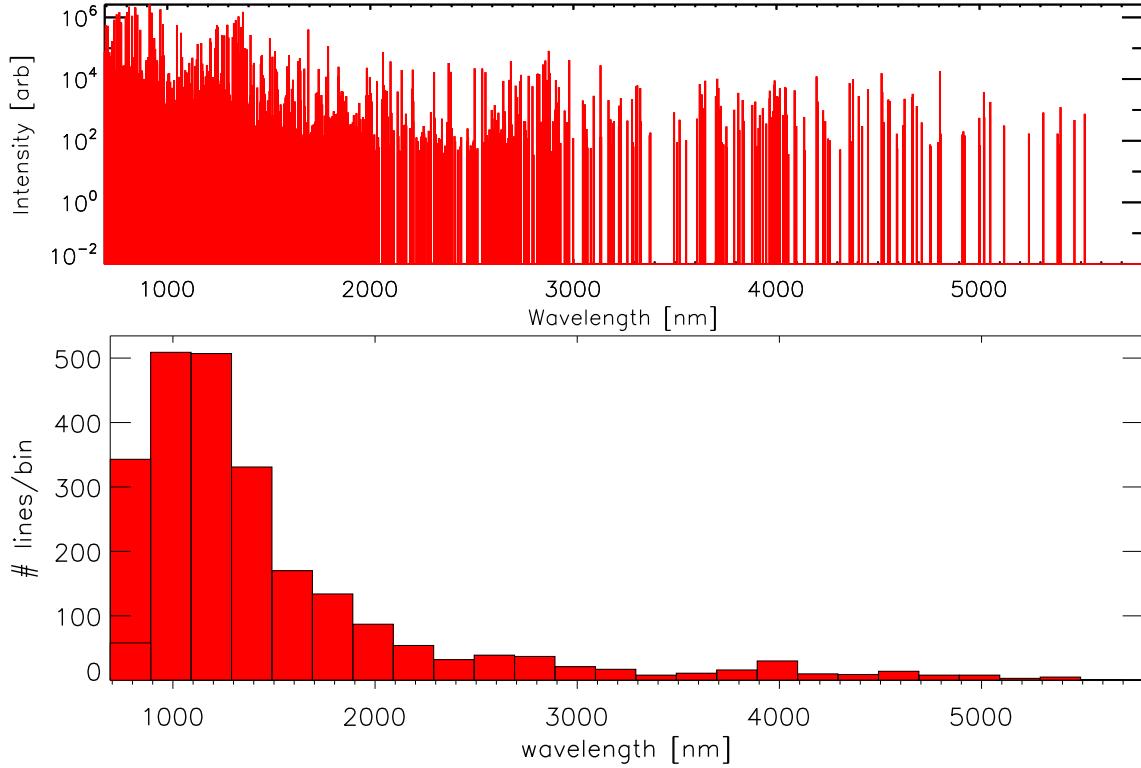


Figure 2. ThAr catalog⁸ (top) and corresponding histogram (bottom) of lines used for the standard CRIRES(+) wavelength calibration. The density of available lines rapidly decreases towards longer wavelengths, rendering ThAr unsuitable as a calibration source for the entire NIR range. ThAr lines greatly vary in intensity, so that effectively only a subset can be used.

CRIRES+ project and its main components are further described elsewhere in these proceedings.^{1, 2, 6, 7} Figure 1 shows an overview of the new optical layout of CRIRES+ and its main components.

This paper focuses on the new absorption gas-cell for CRIRES+, and outlines the wavelength calibration strategy for CRIRES+ comprised of various reference sources. It is organized as follows: §2 describes the wavelength calibration in the NIR and the currently used techniques with CRIRES. In §3, we present a newly developed gas-cell for precision calibration with CRIRES+, and discuss its design, construction, and characterization. The concept for wavelength calibrators with CRIRES+ is described in §4. Concluding remarks are provided in §5.

2. WAVELENGTH CALIBRATION IN THE NIR

High-resolution spectroscopy demands for precise wavelength calibrators. The well established technique in the optical domain using commercially available hollow-cathode lamps (HCLs) such as ThAr provides unresolved emission lines even at the high spectral resolving power of 100 000 offered by CRIRES. ThAr as the default wavelength reference for optical spectrographs can provide a line position accuracy⁹ of 16 – 82 m/s and up to ~ 10 m/s with carefully selected lines¹⁰ in the 400 – 700 nm range for single lines. In a stable environment, ThAr is thus suitable for high-precision applications such as doppler measurements on the m/s scale using large echelle formats. Blended lines and large intensity differences between the metal lines and the lines originating from the fill gas can be handled by careful selection and masking during calibration, however, two major problems exist with HCLs. First, HCLs are intrinsically unstable as their individual line intensities vary from lamp to lamp, and are a function of age, pressure, and operating current. These effects degrade the stability as a reference source. Over their lifetime, the gas pressure inside a HCL decreases, resulting in wavelength changes of the gas lines. The metal lines change in intensities as cathode material is sputtered off, and the geometry of the cathode thus depends on lamp age. Accordingly, the illumination of the instrument by the HCL varies over time. Secondly,

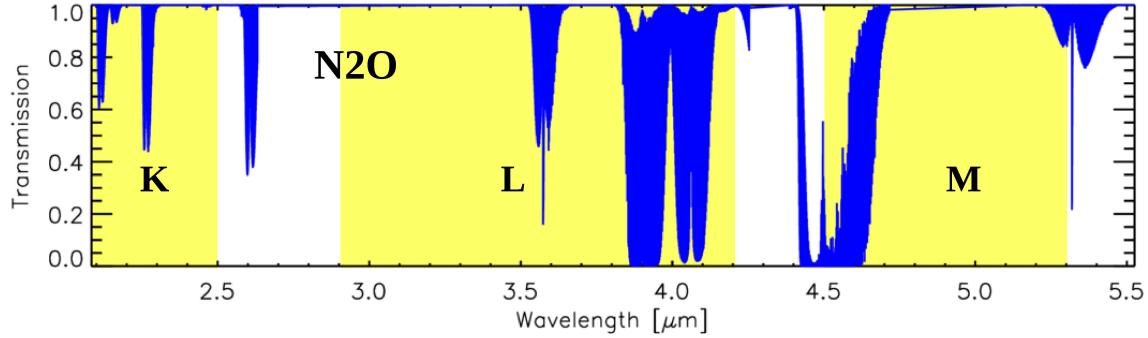


Figure 3. Absorption spectrum of the CRIRES N_2O gas-cell³ in the near-infrared K–L bands. N_2O offers a number of transition bands redwards of $2\mu\text{m}$ as a wavelength reference in selected, small wavelength regions.

ThAr does not exhibit a homogenous density of spectral features in terms of wavelength. While the line density is high in the optical ($\lambda < 1\mu\text{m}$), atomic transitions become infrequent at longer wavelengths. In the NIR, the line density of ThAr decreases so that it is not suitable to provide a wavelength solution for CRIRES beyond $\sim 2.5\mu\text{m}$.¹¹ Nevertheless, a ThAr HCL is a CRIRES general purpose wavelength reference from $0.95 - 2.5\mu\text{m}$, and yields a level of $\sim 50\text{ m/s}$ precision for the line positions. Fig. 2 shows the ThAr emission lines for calibrating CRIRES+ spectra.

As with all NIR spectrographs, wavelength solutions for CRIRES at longer wavelengths rely on sky emission lines, telluric absorption lines, and absorption lines by specialized gases enclosed in reference gas cells. While the hydroxyl night-time airglow (OH) is present over a wide wavelength region in the NIR¹² and well characterized,¹³ at $R = 10^5$ these features are mostly too weak and too infrequent to provide a generally reliable wavelength standard for CRIRES(+). Similarly, molecules present in earth's atmosphere provide a multitude of absorption lines across the NIR, dominated by the strong absorber H_2O , among others, whose transition bands define the boundaries of the band passes. The presence and strength of telluric calibrators, however, are strongly site-dependent and prone to variations on different timescales from hours to years. Thus, a detailed understanding and modelling of the atmospheric conditions, based on simultaneously measured sounding data, is required, as eg. high-altitude winds induce significant uncertainties ($\leq 25\text{ m/s}$) on the line positions.⁸ Telluric molecules such as CO_2 can be used with CRIRES and have demonstrated radial velocity precisions of $5 - 10\text{ m/s}$,¹⁴ but are restricted to narrow wavelength intervals.

The benefits of the wavelength calibration technique using telluric features can be mimicked by exploiting ro-vibration lines from a selected molecular gas. Such a captive gas (or a mixture of several) is then kept under well controlled conditions (inside a gas-cell vessel), and this vessel is brought into the light entering the spectrograph at the time of observations (analogous to the iodine method¹⁵ in the optical domain). The effect of such a gas-cell is thus similar to the imprint of molecular features from the atmosphere, on the actual target spectrum itself, but for selected (non-telluric) species and without the influences of the perturbing dynamical processes in the atmosphere. By using a reference gas in the optical path shared with the light coming from the astronomical target, wavelength calibration exposures can be recorded simultaneously (the gas-cell is illuminated by the target), or offline with a broadband calibration lamp. A detailed knowledge of the reference gas spectrum is generally required, and precise line positions be known from laboratory measurements if absolute calibration is desired. The gaseous absorption lines can then be used to track all instrumental instabilities and drifts that follow the gas-cell in the optical chain. CRIRES has offered two such absorption gas cells for simultaneous and offline calibration. A CO cell to cover the CO bands around $2.1\mu\text{m}$ in the K-band, and a N_2O gas-cell (Fig. 3) with usable absorption features in selected ranges between $2.6 - 4.7\mu\text{m}$.

While the latter approach is a viable option in the L- and M-bands, the range covered by N_2O is very limited. In the K-band, N_2O transition bands are rather weak, while the prominent (and wider) bands in L and M are easily saturated (and thus do not facilitate determination of accurate line positions nor profiles).

The lack of calibration sources in the NIR comparable to those in the visual regime poses a major challenge to the exploitation of these wavelength regions using high-resolution spectroscopy. One of the goals of the

CRIRES+ project is to improve the current wavelength calibration situation. In an on-going effort, we seek to provide enhanced wavelength reference sources for CRIRES+, both for general purpose calibration (of the facility instrument modes) and for specialized applications (high-precision radial velocities in the NIR).

3. THE CRIRES+ PRECISION RADIAL VELOCITY GAS-CELL

The gas-cell wavelength calibration method is the only technique that provides a wavelength reference information and enables monitoring of instrumental effects such as drifts in the dispersion relation and changes in slit illumination *simultaneously* with the astronomical observation, both in time and co-located on the detector. This means that the wavelength solution is recorded at the very same time and under the instantaneous conditions as the stellar light is recorded. Within the instrument, the exact same optical path is used for both the source of wavelength reference and the celestial object, so that the spectral features of both contributions end up on the same pixels in the focal plane. When modelled properly,^{15,16} this approach allows for very high precision (relative) wavelength calibration and long-term repeatability as needed for radial velocimetry work on the m/s level.

For HARPS-type spectrographs, a high degree of illumination stability can be achieved by appropriately feeding the instrument via optical fibers. As CRIRES is not a fiber-fed spectrograph, it is important to provide a stable slit-illumination (aided by the adaptive optics), or to monitor the instrumental profile variations during the observation, by the use of the gas-cell's spectral lines.

For high-precision wavelength calibration with CRIRES+, we have developed a new NIR absorption gas-cell primarily aimed at exoplanet precision Doppler experiments. The design considerations of the reference gas for CRIRES+ are summarized as follows. The filling gas must provide a set of dense, homogenous and sharp spectral lines over a wide wavelength range, as to provide a high density of information usable to construct the dispersion relation. At the same time, the radial velocity information content^{15,17,18} of the stellar spectrum under study must match the anticipated RV precision. This, in turn, is subject to a multitude of parameters, among them attainable SNR of the target observations, availability of spectral features, ie. spectral type, wavelength range and instrumental (spectral) resolution. One of the science drivers⁶ of CRIRES+ is the search of super-Earths around low-mass stars, using the RV technique. To accomplish a ~ 3 m/s level of RV precision for M-stars with CRIRES+ in cross-dispersion, we identified a suitable reference gas that fulfills the requirements in the K-band.

Our choice of filling gas for the CRIRES+ short-path gas-cell is a compound of three molecular species. The mixture is tailored to provide an optimum wavelength coverage in the H and K-bands, with an emphasis on a core region in the K-band. The transmission spectrum is generated by acetylene (C_2H_2), ammonia (NH_3), and an isotopologue of methane ($^{13}CH_4$), and draws from the experience of a previous NH_3 gas-cell for CRIRES,¹⁶ and experiments with methane isotopologues on IRTF/CSHELL.¹⁹ Methane-13 ($^{13}CH_4$) features the carbon atom with an additional neutron compared to naturally abundant methane ($^{12}CH_4$). The latter is a major contributor to the telluric transmission spectrum, and could thus not be disentangled from a captive methane-12 held under controlled conditions (ie. in the gas-cell). However, methane-13 has a different reduced mass due to the heavier nucleus, responsible for shifting its rotational transitions significantly. Methane-13 is a stable isotopologue and is easily distinguished from standard methane-12. An important point is also that methane has well characterized absorption features with high frequency precision.^{20,21} The partial pressures of the three molecular species are listed in Table 1. We have optimized these for the CRIRES+ configuration ($R = 10^5$, ≥ 200 nm continuous wavelength coverage in the K-band, available path-length) to allow for the best “aspect ratio”, ie. the optimum line-depth ($\sim 80\%$) while retaining the smallest possible line-width (unresolved at $R = 10^5$).

3.1 Design and construction

The gas-cell is designed to utilize the maximum available clearance in front of the CRIRES+ instrument cryostat. This renders the length of the cell vessel to be no longer than ≈ 18 cm (constrained by the telescope flange and the instrument derotator), and hence also defines the optical path-length through the reference gas. The gas-cell module is composed of a mounting structure and the actual gas-cell, with the latter being an all-glass cylinder filled with the captive gas mixture. The primary design driver for the cell vessel are a) a longterm, gas-tight sealing (10 years), and b) a high optical efficiency. Experiments have shown that standard viton seals and glued windows cannot provide the long-term stability, and were therefore discarded. Instead, we chose the same

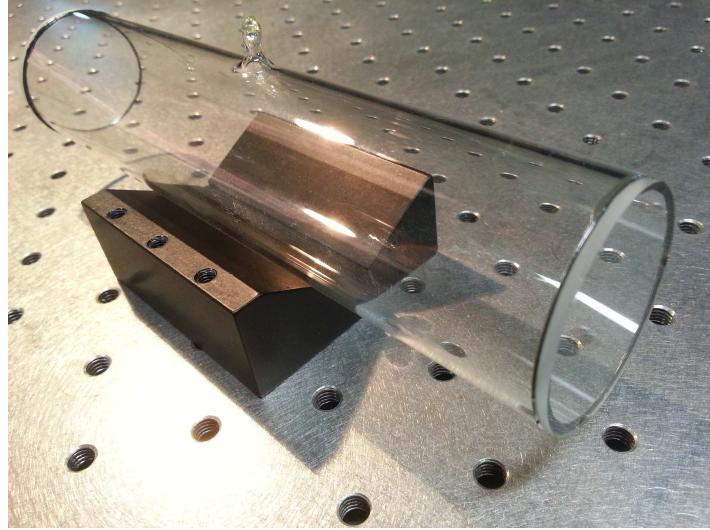


Figure 4. Filled gas-cell cylinder with fritted quartz windows, containing a mixture of $^{13}\text{CH}_4$, NH_3 , C_2H_2 . The “glas nose” on the top middle of the cell is a remainder of the filling stem used to insert the gases.

material (quartz) for both the cylinder and windows, which allows for fritting them together with a glass mold to form a seamless, homogenous joint. The optically polished low-OH quartz glass windows are anti-reflection coated for the K-band, and mutually tilted with respect to each other so that internal fringing effects are minimized. Filling the cell with the appropriate partial gas pressures is done after evacuating the cylinder to below 10^{-3} mbar using a glass stem attached to the cylinder body. The mixture of gases is then achieved by subsequently flooding the cell with the individual species, at the desired partial pressures. Figure 4 shows the sealed and filled gas-cell cylinder.

Our tests over a period of four months have proven that the cell is well sealed, and no change in gas pressure could be detected. Four glas-air interfaces by the two windows inevitably result in a reduced throughput of the instrument. We measured the total transmission of the complete cell to be above 90% in the K-band, and around 85% in the Y-H bands (on average, including windows and gas filling). This only marginally reduces the efficiency of CRIRES+.

3.2 Gas-cell mount

CRIRES(+) features a calibration slide close to the VLT Nasmyth focal plane, before the light enters the derotator and the adaptive optics module. This movable stage holds two slots for gas-cells with short optical path-length that can be inserted directly into the optical beam. The spectral features of the reference gas is thus imprinted onto the stellar light immediately after leaving the telescope. To host the sealed glas vessel in a defined and reproducible location and orientation with respect to the telescope beam, we have designed a specialized mount for the gas-cell (see Figure 5). The glass corpus is fixed in two rings, where four rubber padded screws each

Table 1. Molecular species and their partial pressures for the CRIRES+ precision radial velocity gas-cell. The total pressure of the filled cell is ~ 300 mbar, with a path-length of 18 cm. The fourth column denotes the average line-width of the corresponding species, as measured from high-resolution spectra. In the last column, t gives the percentage of wavelength coverage with usable absorption features deeper than 10% from the gas mixture, for each of the *JHK* band range definitions.

| Molecule | | Pressure [mbar] | line-width [km/s] | t [%] |
|-----------|-----------------------------|--------------------|----------------------|----------------|
| Acetylene | $^{12}\text{C}_2\text{H}_2$ | ~ 60 | 1.791 ± 0.010 | K: $\sim 76\%$ |
| Ammonia | $^{14}\text{NH}_3$ | ~ 90 | 1.978 ± 0.011 | H: $\sim 67\%$ |
| Methane | $^{13}\text{CH}_4$ | ~ 150 | 1.797 ± 0.022 | J: $< 10\%$ |

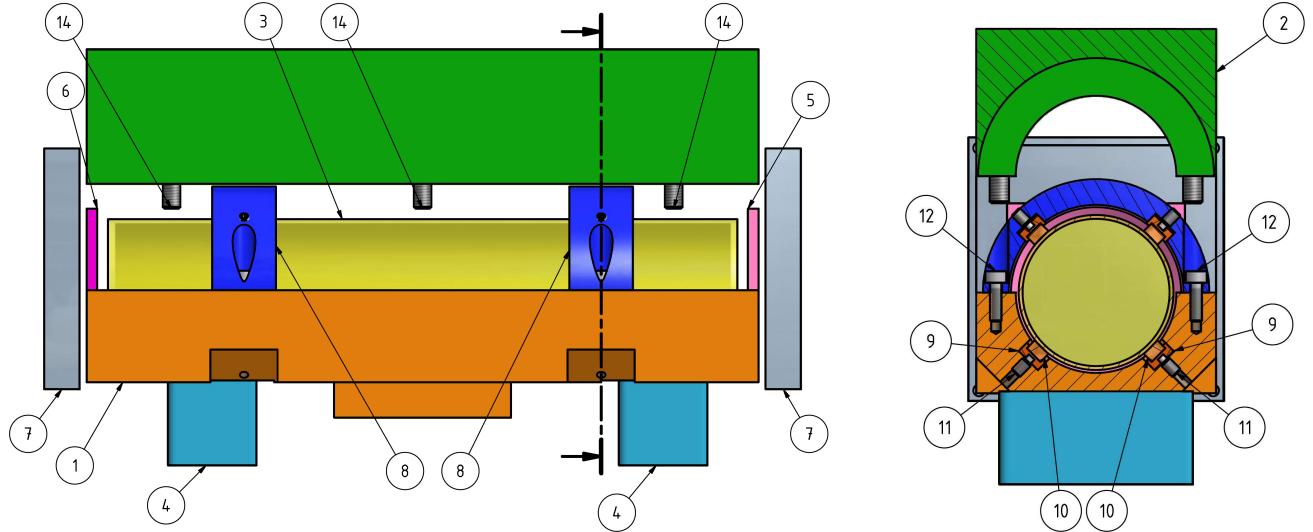


Figure 5. Design of the CRIRES+ short gas-cell mount. The fragile glass cylinder is held in a stress-free configuration. Side view (*left*) and cut front view (*right*). Parts are labelled as follows: protective aluminum shells (1-2), gas-cell cylinder (3), mounting posts and ring fixtures (4, 8), straylight removal masks (5-6), dust protection caps (7), stress-free alignment (9-11), and locking mechanism (12-14).

hold and align the cylinder almost free of stress. This proved especially important during shipping and handling to prevent cracks or breakage of the glass and seals, and ensures long-term endurance under changing ambient conditions. Two aluminum half-shells further protect the cell mechanically and provide shielding from external straylight.

3.3 Laboratory FTS measurements

A prototype gas-cell has been successfully built and filled. We have started to characterize its transmission spectrum by means of a Fourier transform spectrometer (FTS). Spectra of the gas-cell were recorded with a Bruker IFS125HR device at a resolution between $0.04 - 0.0065 \text{ cm}^{-1}$ (corresponding to resolving powers of $250\,000 - 1\,538\,000$ at $1\,\mu\text{m}$). The cell is measured at an ambient pressure $< 0.1 \text{ mbar}$ to suppress the atmospheric contributions by water vapor etc. within the instrument. A blackbody-like continuum lamp is used to illuminate the gas-cell. Normalized spectra of the *H* and *K*-bands are on display in Figures 6 and 7, respectively.

In the H-band ($1.47 - 1.83\,\mu\text{m}$), the strongest absorption features in the cell's spectrum (Figure 6, bottom panel) originate from acetylene in two very deep ($\sim 90\%$) bands around $1.53\,\mu\text{m}$. Similarly prominent contributions in the neighbouring range ($1.5\,\mu\text{m}$) are a set of ammonia lines, partly mixed with acetylene. The largest wavelength range in this band, starting at $1.63\,\mu\text{m}$, is covered by deep ($\leq 80\%$) line systems from methane-13, with minor contributions by ammonia. Overall, the line coverage of the three gases in the H-band is quite complete, with only a small gap around $1.6\,\mu\text{m}$. The upper panels in Figure 6 show FTS spectra of the individual gases ammonia, acetylene, and methane-13. These are measured separately under different ambient conditions, and include some water vapor contributions from a normal atmosphere during the experiment (in the case of NH_3 and C_2H_2). Note that the individual species have lower gas pressures than present in the prototype gas-cell (Table 1). For guidance, the top panel in Figure 6 gives the telluric spectrum of the same FTS setup as measured with the gas-cell, and represents the ambient air from the optical path between source and detector. Note that this telluric spectrum is much weaker and cleaner than a corresponding spectrum measured through Earth's atmosphere with the VLT, due to the much smaller path-length. The shaded areas in Figure 6 denote wavelength ranges outside the H-band definitions.

Our FTS measurements of the K-band ($1.95 - 2.4\,\mu\text{m}$) are plotted in Figure 7. This is the wavelength range for which the gas pressures of ammonia and methane-13 are designed to provide the optimum line depths. Acetylene (third panel from top) has only very weak bands in this range and does not add significantly to

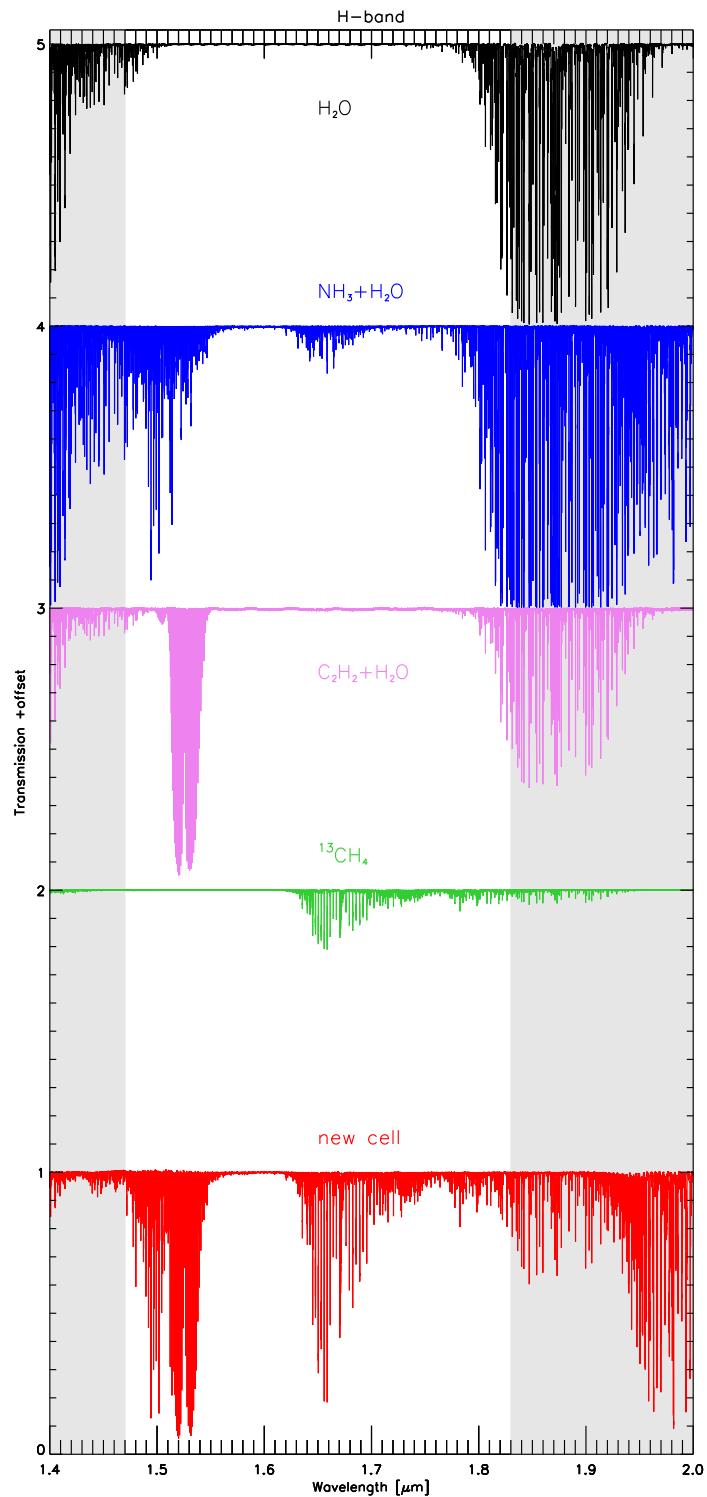


Figure 6. Laboratory FTS measurements of the CRIRES+ gas-cell species in the H-band. Plotted from top to bottom are the ambient atmosphere (mostly contributions by water-vapor, as present during the gas-cell measurement), ammonia and acetylene gas (both including residual water vapor in the setup), methane-13, and the compound gas-cell mixture as measured from the filled CRIRES+ cell.

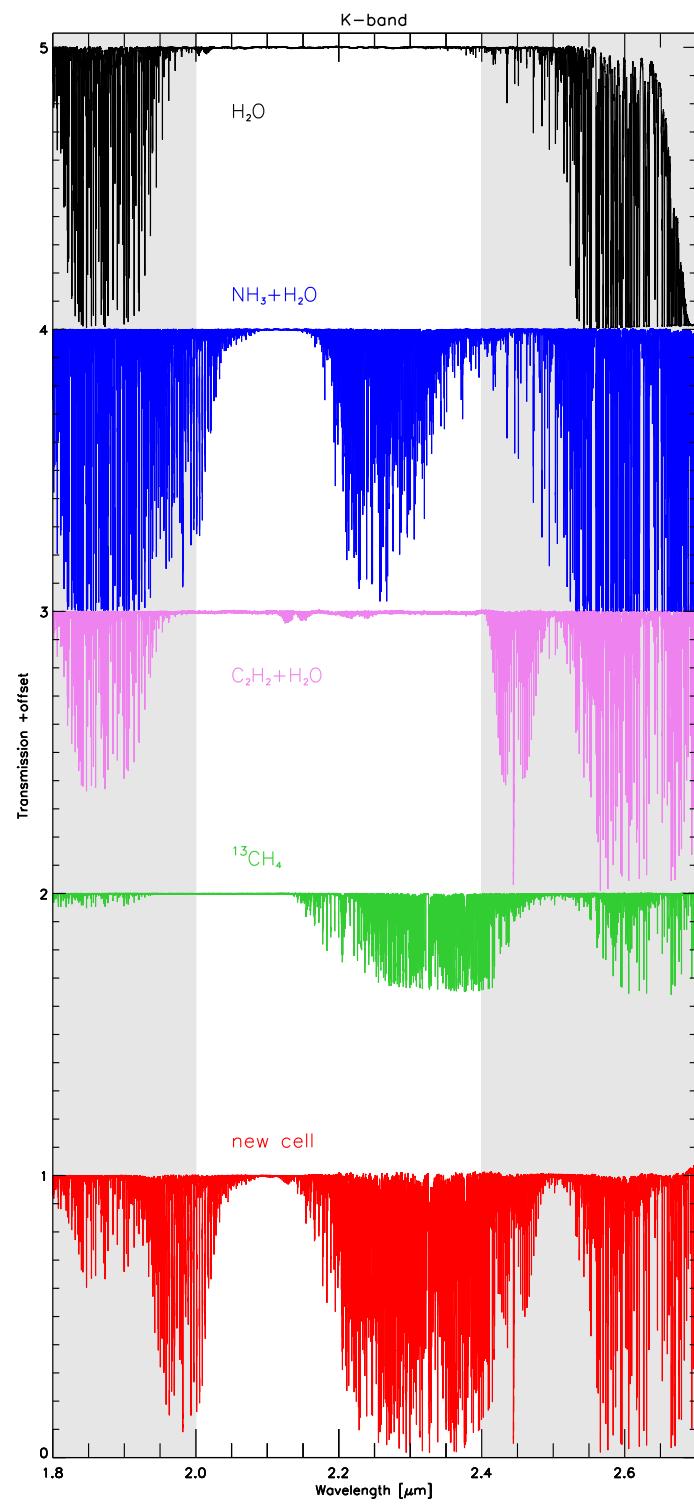


Figure 7. K-band measurements of the filled CRIRES+ gas-cell and its individual species. See Figure 6.

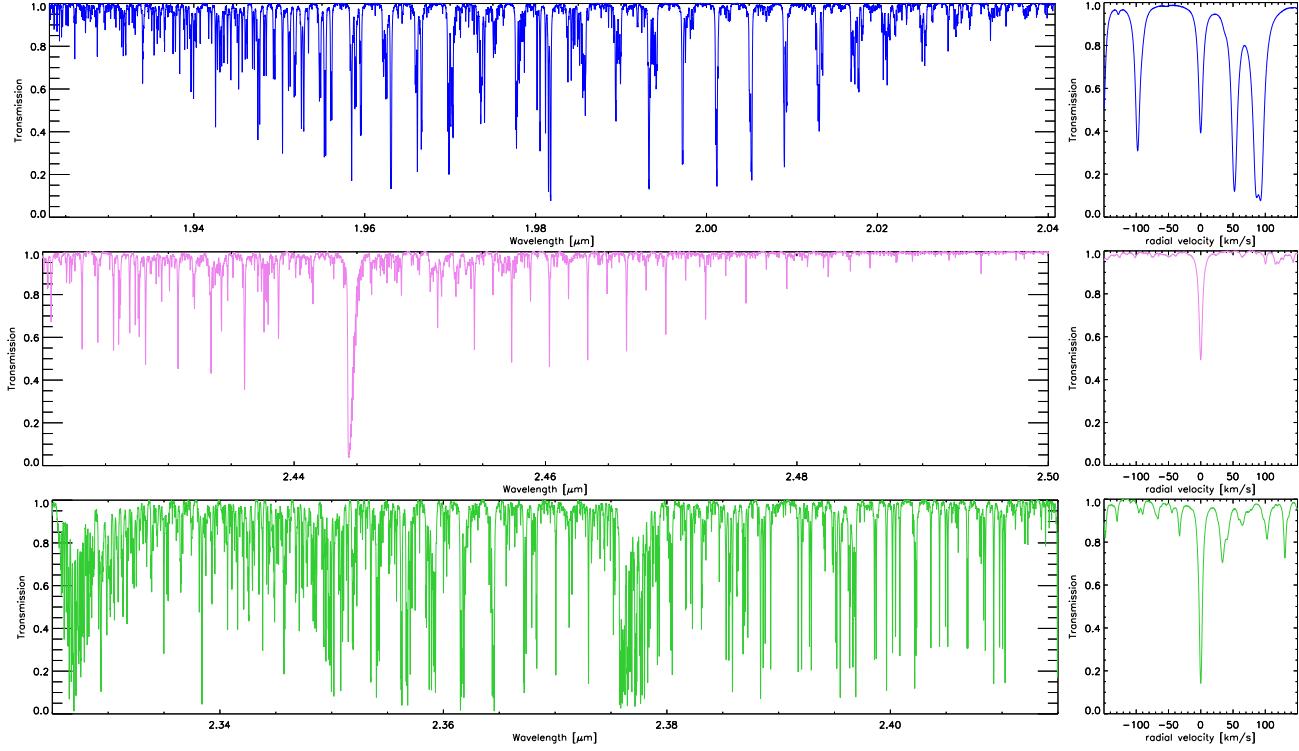


Figure 8. K-band regions with transition bands by ammonia (top, blue), acetylene (middle, pink), and methane-13 (bottom, green) as measured with the filled CRIRES+ cell. Also shown in detail are single line profiles of the corresponding molecule (right panels). In all three regions, some smaller lines from the other two molecules may be present, respectively, as the wavelength regions of their absorption features partly overlap. The line profiles are mostly resolved at the resolution of these FTS measurements ($R = 1\,538\,000$), yet for CRIRES+ ($R = 100\,000$) will qualify as largely unresolved.

the spectrum of the mixture (bottom panel). The major constituent in the K-band is methane-13, achieving large line-depths of more than 95% in the high-resolution FTS spectra. The central part of the band is further populated by strong ammonia lines, which also has features at around $2.0\,\mu\text{m}$ and below. In the K-band, the coverage with reference gas lines is complete but for a $\sim 30\,\text{nm}$ range at $2.1\,\mu\text{m}$. In total, more than 75% of the entire K-band are populated with suitable gas lines deeper than 10% by any of the three reference gas species.

The prototype CRIRES+ gas-cell demonstrates the power of the selected gas mixture in the H and K-bands. For the remaining operating wavelength domains of CRIRES+, other wavelength reference sources are foreseen (Section 4).

To achieve the demanding RV precision of CRIRES+ in the K-band, the spectral lines exploited for wavelength calibration must enable a highly accurate measurement of their line positions. This immediately translates into sharp, unresolved reference lines at the given resolving power ($R = 10^5$) of CRIRES+. Our gas-cell mixture is designed such that the line-widths of all three molecules is smaller than $3\,\text{km/s}$, corresponding to the resolution element of CRIRES+. We measured the line-widths in the FTS spectra with the highest attainable resolution for all three gases in selected, strong absorption bands. At $\Delta\lambda = 0.0065\,\text{cm}^{-1}$ ($R = 1\,538\,000$) these lines are well discernible for $^{13}\text{CH}_4$, NH_3 , and C_2H_2 (though numerous are blended, particularly in $^{13}\text{CH}_4$). Line-widths are typically closely distributed around $2\,\text{km/s}$ (cf. Table 1), with very similar average widths of $1.797 \pm 0.022\,\text{km s}^{-1}$, $1.978 \pm 0.011\,\text{km s}^{-1}$, and $1.791 \pm 0.010\,\text{km s}^{-1}$ (for $^{13}\text{CH}_4$, NH_3 , and C_2H_2 , respectively). Figure 8 shows these transmission features in narrow regions of the K-band separately for all three constituents, and also illustrates corresponding typical line profiles.

4. WAVELENGTH CALIBRATION STRATEGY FOR CRIRES+

CRIRES+ will be a facility instrument at the VLT, addressing a large variety of scientific questions. Appropriate wavelength calibration sources must be provided for the entire working range of the spectrograph ($0.95 - 5.3\mu\text{m}$). Moreover, wavelength calibration needs to support all observing modes of CRIRES+. In combination with the limited wavelength coverage of the individual sources, this leads to a number of constraints the CRIRES+ calibration plan must match:

1. The existing HCL techniques as well as the gas-cells (including the new CRIRES+ cell) cannot operate in polarimetry mode. This is a result of the opto-mechanical layout, where all calibration devices are located on a movable stage in front of the Nasmyth focus. At the same time, the polarimeter unit⁷ is also located on the same stage, and thus cannot be inserted at the same time as the gas-cells or the HCL fiber-feeds.
2. The ThAr HCL is only suitable for the Y–K bands (see Section 2).
3. The available and new gas-cells lack broadband coverage in, or do not operate in the Y–J and L–M bands.
4. The available techniques in the L–M bands are not satisfactory (Section 2).

We address these issues by expanding the suite of calibration sources for CRIRES+. The concept for calibrators comprises the following changes and additions. First, the ThAr HCL will be superseded by an UNe HCL. The characteristics of UNe have recently been studied, and prove to be very comparable to ThAr. A major advantage of UNe is that it provides significantly more lines (three to five times) in the NIR, and thus increases the suitability of the HCL method for CRIRES+ in the J, H, and K-bands. UNe catalogs^{22–24} are now available with line lists covering the Y–L bands. These HCLs are readily available and their line density is suitable for CRIRES+ as a general purpose calibrator up to (including) the K-band, where the transmission of commercially available UNe bulbs, due to the quartz window, in combination with standard optical fibers breaks down. The implementation of the UNe HCL in CRIRES+ (aided by the cross-dispersed spectral format) will significantly improve the dispersion solution.

Secondly, to enable wavelength calibration for polarimetric observations, an additional reference source with high stability coverage is considered. Etalons provide a homogeneously spaced set of lines, where the line sharpness (“finesse”) and contrast can be controlled by the quality and reflectivity of the reflective coating. At the same time, the peak-to-peak distance (free spectral range) is a function of the cavity length. This allows to tune the free spectral range to the resolution of the instrument. For CRIRES+, we are developing stabilized Fabry-Pérot étalons to provide suitable offline calibration lines over the entire NIR range. Two etalon units are studied, where their usable wavelength range is driven by the availability of suitable broadband cavity coatings. Although a small finesse (~ 10) satisfies a level of 5 m/s calibration precision, a broadband performance over several NIR bands (eg. YJ and HK) is not easily achieved. Furthermore, challenges include achieving the necessary long-term stability of such a unit. The stability is directly linked to the temperature stability of the etalon, and thus demands for an actively controlled environment inside a vacuum tank. For CRIRES+, fiber-fed étalons are under study. This poses stringent requirements on the etalon illumination and its stability by the optical fibers. A quasi-continuum laser-driven light source (LDLS) is used to provide the necessary white-light to the etalon. These FP étalons are compatible with the CRIRES+ polarimetric modes when the calibration light is fed into the optical path before the movable stage, where the polarimeter is mounted on. This can be accomplished by exploiting the existing calibration unit outside of the telescope beam. The output light of that unit is redirected into the beam by a folding mirror, before the movable stage. To obtain an absolute wavelength solution with the etalon, the UNe HCL will be employed as a reference. This is because the line-position of the etalon peaks is not known *a priori* (albeit their relative positions are), but can be assigned by comparison with a HCL line. The development of an etalon for CRIRES+ will significantly enhance its dispersion solution across the entire spectral format, by providing homogeneously and densely distributed reference lines. With a dedicated and optimized etalon unit, this technique may also overcome the lack of calibrators in the L and M-bands.

In a third approach, we are also seeking to further advance the gas-cell design and to expand the spectral coverage beyond the H and K-bands. Absorption gas-cells with an increased optical path-length to several meters are under study. Such a cell could be operated with filling gases at much lower pressures, yielding significantly

reduced line-widths for gasous species that at short path-lengths a) provide unsuitably broad spectral lines, or b) have too weak absorption features due to small absorption coefficients.

The CRIRES+ suite of wavelength reference sources also comprises the existing N₂O gas-cell for use in selected L&M wavelength ranges. Also supported are the established methods of using sky lines and telluric lines to construct the dispersion solution in wavelength domains where applicable (cf. Section 2).

5. CONCLUSION

The CRIRES+ project will upgrade VLT/CRIRES into a cross-dispersed, high-efficiency NIR spectrograph at a resolving power of 10⁵. New capabilities such as high-precision radial velocity measurements on low-mass stars and polarimetric observations call for new and improved wavelength calibration techniques across the operating domain from 1 – 5 μm.

To satisfy the corresponding requirements, we have developed a new CRIRES+ absorption gas-cell specifically tailored to enable RV experiments with M-stars on the 3 m/s level in the K-band. We have designed, built, and characterized a prototype gas-cell for CRIRES+ filled with a compound of ammonia, acetylene, and methane-13 molecular species. This cell provides a forest of absorption lines in the H and K-bands for simultaneous wavelength calibration, evidenced in high-resolution FTS spectra. Our data show that the population of lines covers a high fraction of the bandpasses, and that the gas line-widths are smaller than can be resolved with CRIRES+, thus providing high-precision wavelength markers.

We have also outlined the wavelength calibration strategy and our developments to expand the suite of frequency calibration sources for CRIRES+. This includes an improved UNe-HCL over ThAr, the new gas-cell for precision applications, and the design of Fabry-Pérot étalons to cover the Y–M bands. The set of advanced wavelength calibrators will enable CRIRES+ to explore the NIR regime in unprecedented detail.

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REFERENCES

- [1] Oliva, Ernesto et al., “Concept and optical design of the cross-disperser module for CRIRES+,” *Proceedings of the SPIE*, 9147-289 (2014).
- [2] Lizon, Jean-Louis et al., “Opto-mechanical design of a new cross dispersion unit for the CRIRES+ high resolution spectrograph for the VLT,” *Proceedings of the SPIE*, 9147-290 (2014).
- [3] Käufl, H.-U., Ballester, P., Biereichel, P., Delabre, B., Donaldson, R., Dorn, R., Fedrigo, E., Finger, G., Fischer, G., Franzia, F., Gojak, D., Huster, G., Jung, Y., Lizon, J.-L., Mehrgan, L., Meyer, M., Moorwood, A., Pirard, J.-F., Paufique, J., Pozna, E., Siebenmorgen, R., Silber, A., Stegmeier, J., and Wegerer, S., “CRIRES: a high-resolution infrared spectrograph for ESO’s VLT,” in [Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series], Moorwood, A. F. M. and Iye, M., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **5492**, 1218–1227 (Sept. 2004).
- [4] Paufique, J., Biereichel, P., Donaldson, R., Delabre, B., Fedrigo, E., Franzia, F., Gigan, P., Gojak, D., Hubin, N. N., Kasper, M. E., Kaeufl, H.-U., Lizon, J.-L., Oberti, S., Pirard, J.-F., Pozna, E., Santos, J., and Stroebele, S., “MACAO-CRIRES: a step toward high-resolution spectroscopy,” in [Advancements in Adaptive Optics], Bonaccini Calia, D., Ellerbroek, B. L., and Ragazzoni, R., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **5490**, 216–227 (Oct. 2004).
- [5] Dorn, R. J., Finger, G., Huster, G., Kaeufl, H.-U., Lizon, J.-L., Mehrgan, L., Meyer, M., Pirard, J.-F., Silber, A., Stegmeier, J., and Moorwood, A. F. M., “The CRIRES InSb megapixel focal plane array detector mosaic,” in [Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series], Garnett, J. D. and Beletic, J. W., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **5499**, 510–517 (Sept. 2004).

- [6] Follert, Roman et al., "CRIRES+: a cross-dispersed high resolution infrared spectrograph for the ESO VLT," *Proceedings of the SPIE*, 9147-44 (2014).
- [7] Lockhart, Matthew et al., "Novel infrared polarimeter for the ESO CRIRES+ instrument," *Proceedings of the SPIE*, 9147-329 (2014).
- [8] Kerber, F., Nave, G., Sansonetti, C. J., and Bristow, P., "From laboratory to the sky: Th-Ar wavelength standards for the cryogenic infrared echelle spectrograph (CRIRES)," *Physica Scripta Volume T* **134**, 014007 (May 2009).
- [9] Palmer, B. A. and Engleman, R., *[Atlas of the Thorium spectrum]* (1983).
- [10] Lovis, C. and Pepe, F., "A new list of thorium and argon spectral lines in the visible," *A&A* **468**, 1115–1121 (June 2007).
- [11] Kerber, F., Nave, G., and Sansonetti, C. J., "The Spectrum of Th-Ar Hollow Cathode Lamps in the 691–5804 nm region: Establishing Wavelength Standards for the Calibration of Infrared Spectrographs," *ApJS* **178**, 374–381 (Oct. 2008).
- [12] Rousselot, P., Lidman, C., Cuby, J.-G., Moreels, G., and Monnet, G., "Night-sky spectral atlas of OH emission lines in the near-infrared," *A&A* **354**, 1134–1150 (Feb. 2000).
- [13] Abrams, M. C., Davis, S. P., Rao, M. L. P., Engleman, Jr., R., and Brault, J. W., "High-resolution Fourier transform spectroscopy of the Meinel system of OH," *ApJS* **93**, 351–395 (July 1994).
- [14] Figueira, P., Pepe, F., Melo, C. H. F., Santos, N. C., Lovis, C., Mayor, M., Queloz, D., Smette, A., and Udry, S., "Radial velocities with CRIRES. Pushing precision down to 5–10 m/s," *A&A* **511**, A55 (Feb. 2010).
- [15] Butler, R. P., Marcy, G. W., Williams, E., McCarthy, C., Dosanjh, P., and Vogt, S. S., "Attaining Doppler Precision of 3 M s⁻¹," *PASP* **108**, 500 (June 1996).
- [16] Bean, J. L., Seifahrt, A., Hartman, H., Nilsson, H., Wiedemann, G., Reiners, A., Dreizler, S., and Henry, T. J., "The CRIRES Search for Planets Around the Lowest-mass Stars. I. High-precision Near-infrared Radial Velocities with an Ammonia Gas Cell," *ApJ* **713**, 410–422 (Apr. 2010).
- [17] Bouchy, F., Pepe, F., and Queloz, D., "Fundamental photon noise limit to radial velocity measurements," *A&A* **374**, 733–739 (Aug. 2001).
- [18] Reiners, A., Bean, J. L., Huber, K. F., Dreizler, S., Seifahrt, A., and Czesla, S., "Detecting Planets Around Very Low Mass Stars with the Radial Velocity Method," *ApJ* **710**, 432–443 (Feb. 2010).
- [19] Anglada-Escudé, G., Plavchan, P., Mills, S., Gao, P., García-Berriós, E., Lewis, N. S., Sung, K., Ciardi, D., Beichman, C., Brinkworth, C., Johnson, J., Davison, C., White, R., and Prato, L., "Design and Construction of Absorption Cells for Precision Radial Velocities in the K Band Using Methane Isotopologues," *PASP* **124**, 586–597 (June 2012).
- [20] Nai-Cheng, S., Yao-Xiang, W., Yi-Min, S., Cheng-Yang, L., Xue-Bin, Z., and Chu, W., "Iodine and Methane Stabilized He-Ne Lasers as Wavelength Standards," in *[Precision Measurement and Fundamental Constants]*, Taylor, B. N. and Phillips, W. D., eds., 77 (Aug. 1981).
- [21] Boudon, V., Champion, J.-P., Gabard, T., Loëte, M., Coustenis, A., de Bergh, C., Bézard, B., Lellouch, E., Drossart, P., Hirtzig, M., Negrão, A., and Griffith, C. A., "Methane in Titan's atmosphere: from fundamental spectroscopy to planetology," *Europhysics News* **40**, 17–20 (July 2009).
- [22] Redman, S. L., Lawler, J. E., Nave, G., Ramsey, L. W., and Mahadevan, S., "The Infrared Spectrum of Uranium Hollow Cathode Lamps from 850 nm to 4000 nm: Wavenumbers and Line Identifications from Fourier Transform Spectra," *ApJS* **195**, 24 (Aug. 2011).
- [23] 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," *ApJS* **199**, 2 (Mar. 2012).
- [24] Sarmiento, Luis-Fernando, Reiners, Ansgar, Seemann, Ulf et al., "Characterizing UNe hollow cathode lamps at NIR wavelengths for the CARMENES survey," *Proceedings of the SPIE*, 9147-194 (2014).