Near-infrared calibration systems for precise radial-velocity measurements

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ABSTRACT

We present work done to prepare two new near-infrared calibration sources for use on high-precision astrophysical spectrographs. Uranium-neon is an atomic calibration source, commercially available as a hollow-cathode lamp, with over 10 000 known emission lines between 0.85 and 4 μm. Four gas cells — containing C_2H_2, $H^{13}CN$, ^{12}CO, and ^{13}CO, respectively — are available as National Institute of Standards and Technology (NIST) Standard Reference Materials (SRMs), and provide narrow absorption lines between 1.5 and 1.65 μm. These calibration sources may prove useful for wavelength-calibrating the future near-infrared high-precision radial-velocity spectrometers, including the Calar Alto high-Resolution search for M dwarfs with Exo-earths with a Near-infrared Echelle Spectrograph (CARMENES),[1] the SpectroPolarimetre InfraROUge (SPIRou) * , and the Habitable-Zone Planet Finder (HPF).[2]

Keywords: near infrared, calibration, radial velocities, atomic spectra, molecular spectra, exoplanets

1. INTRODUCTION

The radial velocity technique for identifying exoplanet candidates has contributed to the majority of the confirmed exoplanets known to date. As exoplanet detection techniques and technology continue to improve, astronomers are detecting lower-mass planets. The discovery and characterization of potentially-habitable Earth-mass planets is a primary goal for upcoming spectrographs such as the Habitable-Zone Planet Finder (HPF),[2] the SpectroPolarimetre InfraROUge (SPIRou) * , and the Calar Alto high-Resolution search for M dwarfs with Exo-earths with a Near-infrared Echelle Spectrograph (CARMENES).[1] These spectrographs require high-precision calibration sources to distinguish the stellar radial velocity signal from drifts in the spectrograph wavelength scale. Current atomic and molecular standards have typical uncertainties of a few parts in 10^8. If the spectral lines from the calibration sources are precise and dense enough, they can also be used to identify non-uniform spacing in the pixels (caused in manufacturing).[3]

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There are several promising calibration sources for the near-infrared, including laser frequency combs,[4,5] thorium argon hollow-cathode lamps (HCLs),[6] uranium neon (U/Ne) HCLs,[7] telluric absorption lines,[8,9] a fiber Fabry Pérot (see Halverson et al., this proceedings), and a variety of molecular absorption lines.[10,11] At the National Institute of Standards and Technology (NIST), we have measured the wavelengths of U/Ne emission lines and several gas cells, using archival data and the NIST 2-m Fourier transform spectrometer (FTS). We have received technical time to test and characterize these sources on the European Southern Observatory's (ESO's) CRyogenic high-resolution InfraRed echelle Spectrograph (CRIRES),[12] which we will utilize this fall.

This conference paper is organized as follows. §2 describes the recently-calibrated uranium neon emission spectrum. In §3, we describe some of the tests we have done to prepare for a calibration run on CRIRES in the fall. In §4, we compare the usefulness of these two calibration sources and what we intend to measure in the near future. We provide concluding remarks in §5.

2. URANIUM NEON

Uranium neon is available as a hollow-cathode lamp from Photron†. These lamps can be run at a range of currents, but are typically rated to run at 15 mA. Running the lamps at higher currents results in an enhancement in the strength of the metal lines over the gas lines,[13] but reduces the lamp lifetimes (HCLs typically last for 5000 mA-hours). The neon lines are not as useful for precise wavelength calibration because their wavelengths depend upon the gas pressure. The pressure decreases as the lamp is used due to trapping of gas atoms to the lamp envelope by sputtered cathode material. The line intensities change as the lamp ages, especially as the lamp nears the end of its life,[14] but we have no reason to believe that the wavelengths of the metal lines will change as the gas pressure decreases.

Measuring any change in the wavelengths of the metal lines as the lamp ages is particularly difficult, because the best way to do so would be to use a simultaneous, absolute wavelength calibration standard. Such a source would need to illuminate the spectrograph in the same manner as the cathode. Even the gas and metal lines from the same hollow cathode can illuminate the same spectrograph in different ways, since the gas lines originate from a wider region than the metal lines. As the lamp ages, the inner diameter of the cathode grows larger, changing the way the metal lines illuminate the spectrograph. This will be true even for fiber-fed spectrographs, if the fiber feed does not utilize a double-scrambler.[15]

Using archival FTS data from Kitt Peak, several of us measured the line positions and uncertainties of over 10 000 uranium lines between 1 and 5 μm.[7] This is a factor of ≈ 4 increase in the number of available calibration lines compared to the currently-measured thorium lines in the same spectral region.[6] A comparison with the line densities of thorium,[6] neon,[16] and argon[17,18] standards are presented in Figure 1.[7] The top two panels of Figure 2 show a comparison between a Th/Ar hollow cathode lamp (measured on the NIST 2-m FTS) and a U/Ne hollow cathode lamp (measured on the PSU Pathfinder spectrograph) between 1500 and 1600 nm. Both signal-to-noise ratio scales are linear between 0 and 10, and logarithmic above 10, to help highlight the high density of fainter emission lines.

It should be noted that a greater line density does not necessary correspond to more precise radial velocities, as line blending at lower resolutions will increasingly create systematic shifts in the line centers. Spectral atlases can sometimes be used to estimate expected line densities at particular resolutions. If independent calibration sources are available (such as laser frequency combs[19]), they can be used to identify which lines provide accurate wavelength calibrations.[5]

Uranium neon lamps are the planned calibration source for use in HPF (Mahadevan et al, this proceedings), and are already in use by the Sloan Digital Sky Survey III (SDSS-III) Apache Point Observatory Galactic Evolution Experiment (APOGEE) spectrograph.[20]

†Identification of specific products is for scientific information only and does not constitute an endorsement by NIST.

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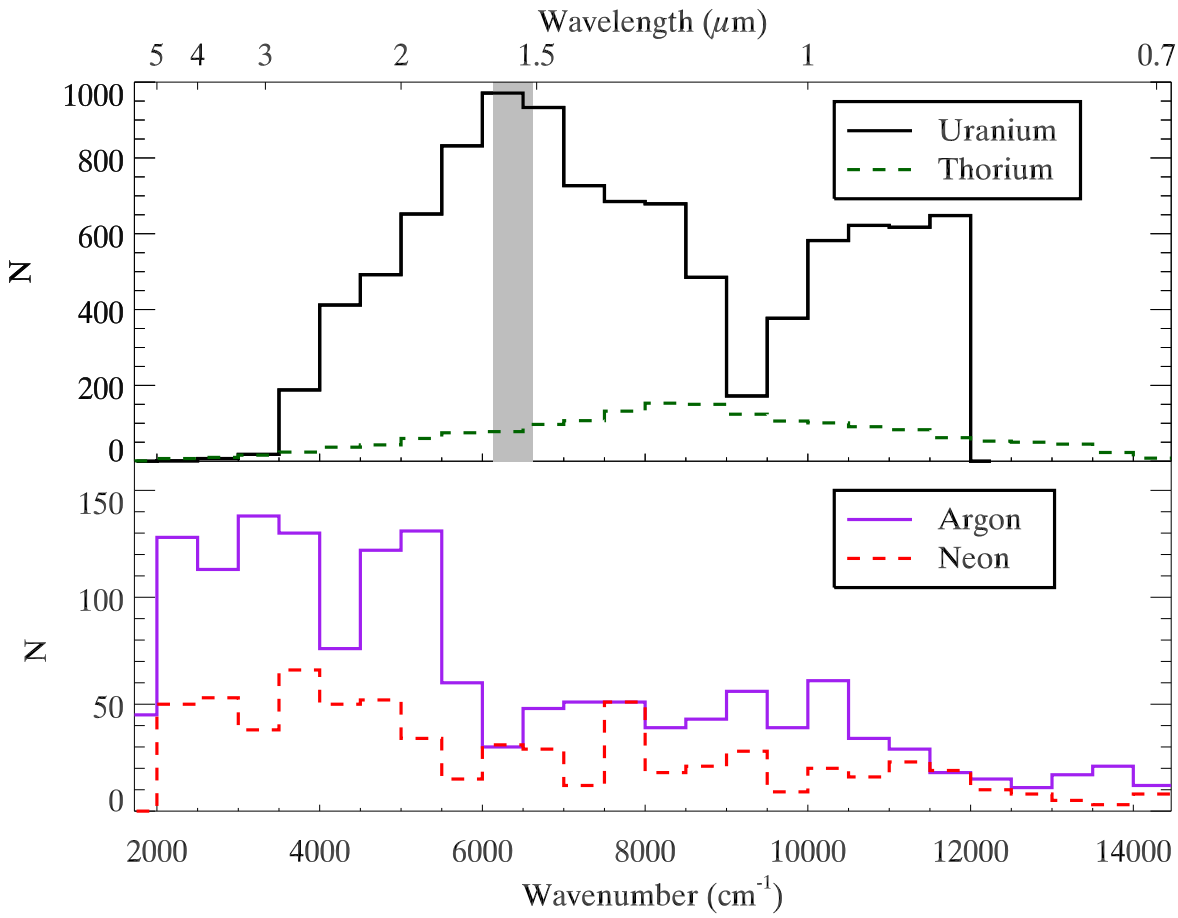

Figure 1. The line densities for uranium, thorium, argon, and neon lines in the NIR. N is the number of lines per 500 cm^{-1}. Note that the observed line density will depend upon the sensitivity of your spectrometer. Echelle spectrographs, for example, are much more sensitive than the FTSs that were utilized to measure these lines, so many fainter, unmeasured lines may be visible. **Top:** Histograms of the uranium[7] and thorium[6] lines in the NIR. The shaded area indicates the spectral coverage of the four NIST SRMs. The large gap in the number density of uranium lines around 9250 cm^{-1} corresponds to a gap in the archived data used to populate the line list. The drop in the number of uranium lines above 12000 cm^{-1} indicates the limit of the line list. **Bottom:** The same, but for argon[17,18] and neon standards.[16] In general, neon is a more desirable fill gas for hollow cathode lamps in this spectral region, because there are fewer lines and they are also not as bright as the argon lines in the NIR.

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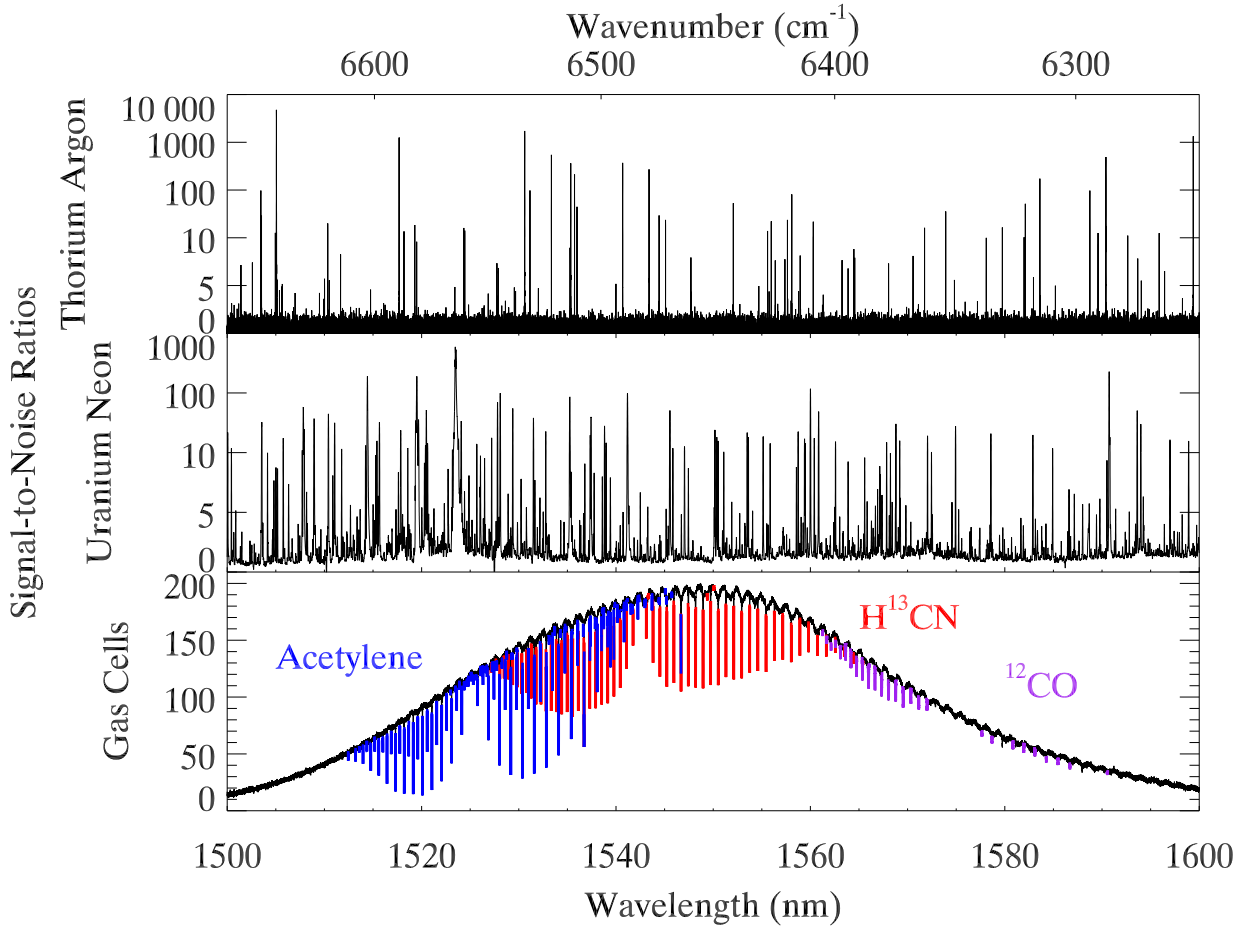

Figure 2. A comparison of spectra of a thorium-argon hcl (top), a uranium-neon hcl (middle), and three NIST SRM gas cells (bottom). The hollow cathode signal-to-noise ratio scales are linear between 0 and 10, and logarithmic above 10. The Th/Ar spectrum was measured on the FTS with a hollow cathode run at 20 mA. The U/Ne spectrum was made on the PSU Pathfinder spectrograph with a hollow cathode running at 14 mA. The gas cell spectra were taken on the NIST 2-m FTS. The absorption lines of C_2H_2 (blue), $H^{13}CN$ (red), and ^{12}CO (cyan) are visible throughout this region. Some of the gas cell lines overlap (even at this resolution of 0.015 cm^{-1}. Note the prominent spectral ripple of the SLED. This spectral ripple is caused by back-reflections between the chip facet and the fiber, and is temperature-dependent. Our SLED is temperature-stabilized to 0.01 K.

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3. TELECOMMUNICATIONS GAS CELLS

NIST has characterized four Standard Reference Materials (SRMs)[‡] for use by the telecommunications industry[21–23] (see Figure 3). These four gases — C_2H_2, hydrogen cyanide, and two isotopes of carbon monoxide — provide a forest of narrow, deep absorption lines across the near-infrared H-band, from 1.5 to 1.65 μm. Since these sources are available coupled to single-mode fibers, it is not sensible to insert them in the stellar beam path (as is typical for other gas cells, such as iodine, N_2O, HF, or tellurium), but rather to illuminate them via a stable continuum source and use them in a manner similar to the way thorium argon or uranium neon are used to calibrate spectrographs — either by flanking the stellar spectrum in a fiber-fed spectrograph, or by taking calibration spectra immediately before and after stellar spectra. Custom-made cells could be fitted with multi-mode fibers, which would allow them to be used in the stellar beam path of fiber-fed spectrographs. Since these gases are kept in independent cells, they can be used in series in any desired combination. These gas cells are insensitive to vibration and variations in the polarization of the continuum source. Table 1 summarizes information about the gas cells, including the cell pressures of the NIST SRMs, and the quantity of gas in each cell.

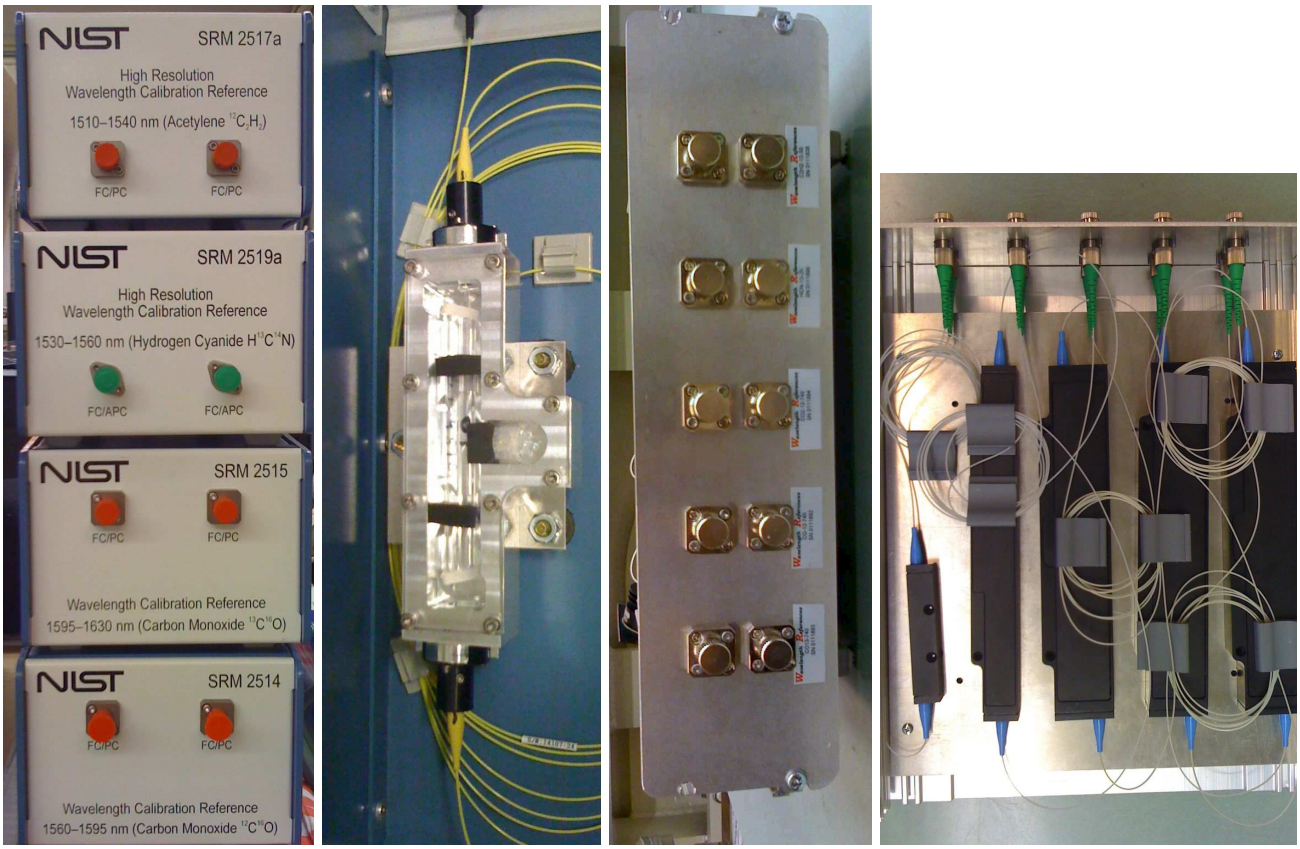

Figure 3. From left to right: The housing for the four NIST SRMs; the NIST SRM C_2H_2 cell inside its housing; a custom-made housing for all of the gas cells; the interior of our custom-made gas cell housing. The gas cells can be used individually, or can be joined in series to imprint the continuum spectrum with absorption lines from several sources.

We have measured the absorption spectra of each of these cells using a super-luminescent light-emitting diode (SLED) as a continuum source. The spectrum of three of these cells is shown in the bottom panel of Fig. 2. Each spectrum is highlighted with a different color (blue for C_2H_2, red for $H^{13}CN$, and purple for ^{12}CO). The envelope function is defined primarily by the SLED, but different optical fibers have different transmission curves, which

[‡]www.NIST.gov/srm/

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Gas	Cell Pressure (kPa)	SRM Number
$H^{13}CN$	3.3	2519a
^{12}CO	133	2514
^{13}CO	133	2515
C_2H_2	6.7	2517a

Table 1. A summary of the four NIST SRMs, their gas pressures (in kilopascals), and their SRM numbers.

introduce low-frequency oscillations to the spectrum. The high-frequency ripple in the SLED spectrum is caused by back-reflections off the chip facets and the fiber. The spectrum of this ripple is temperature-dependent, but in principle can be subtracted from the spectrum provided that the SLED is thermally-stabilized to about 0.01 K.

In principle, any continuum source that covers the H-band could be used to illuminate the cells. The SLED proved especially useful for our experiments on the NIST 2-m FTS because SLEDs are built to efficiently couple light into a single-mode fiber. We also tested a few super-continuum sources, but the pulse rate of these sources were comparable to our FTS sampling rate, which greatly reduced the S/N that we could achieve.

The radial velocity precision that can be obtained from a given absorption spectrum (whether it is the calibration spectrum or the stellar spectrum) in the photon-limited regime is given by:[24]

$$\delta V_{rms} = \frac{c}{S/N\ Q} \tag{1}$$

where c is the speed of light, S/N is the signal-to-noise ratio of the spectrum, and Q is the quality factor of the spectrum. The quality factor is defined to be:

$$Q = \sqrt{\frac{\sum W(i)}{\sum I(i)}} \tag{2}$$

where $I(i)$ is the intensity of the spectrum in pixel i, and $W(i)$ is the weight of each pixel, given by:

$$W(i) = \frac{\lambda^2(i)(\partial I(i)/\partial\lambda(i))^2}{I(i) + \sigma^2} \tag{3}$$

where λ is the wavelength of light falling on the pixel i, $\partial I(i)/\partial\lambda(i)$ is the slope of the spectrum at pixel i, and σ is the detector noise. Note that Q is proportional to the sum of the slopes of the spectrum — so deeper and narrower absorption lines provide more precise radial velocity measurements.

We have estimated the quality factor for $H^{13}CN$, C_2H_2, and ^{12}CO (see Figure 4) in this manner. These spectra were taken with the NIST 2-m FTS at a variety of resolving power ($\lambda/\delta\lambda$) between 13 000 and 655 000. While the quality factor is usually a quantity that is calculated from a theoretical spectrum, one can also estimate the quality factor with high-S/N spectra, as long as the continuum is smoothed or ignored — since photon noise in the continuum will add to the quality factor. After normalizing the spectrum, the continuum was set to 1 where there were no spectral lines.

As can be seen in Fig. 4, C_2H_2 has the highest quality factor, which is not surprising, considering that it has the deepest absorption lines. $H^{13}CN$ has the next highest quality factor, followed by ^{12}CO. ^{13}CO has a very similar spectrum to ^{12}CO, and thus has a similar quality factor at these resolutions. Note that the measured quality factor of $H^{13}CN$ is in good agreement with the theoretical Q factor shown in figure 3 of Mahadevan & Ge, 2009.

The largest source of uncertainty in the absorption line wavelengths is the fill pressure. As the pressure in the cell rises, elastic collisions between the molecules shift the absorption line centers linearly. The pressure shift

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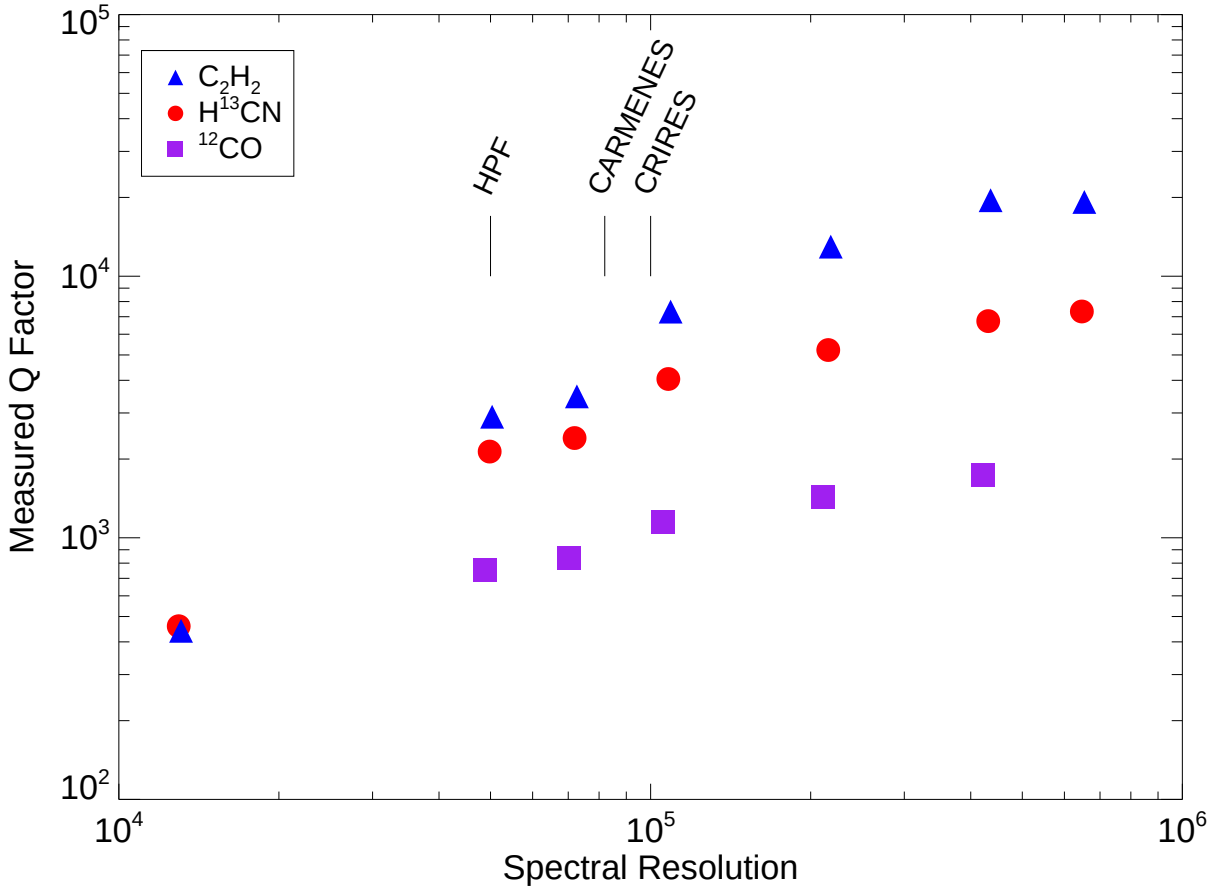

Figure 4. The quality factor (see Equation 2) for C_2H_2, $H^{13}CN$, and ^{12}CO. As expected, the gases with the deepest absorption lines (see Figure 2) have the highest quality factors. These quality factors were calculated using high-S/N spectra of each of the individual gas cells at the spectral resolutions shown. The measured $H^{13}CN$ quality factors are in good agreement with the Q factors calculated by Mahadevan & Ge (2009) (see their figure 3). The spectral resolutions of three spectrographs mentioned in this proceedings are indicated with vertical lines.

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slopes are different for each line and depend on the cell temperature. The pressure shift slopes of several of these lines have been measured by NIST Boulder at 22 °C ± 2 ° C.[21–23] In theory, the pressure of the gas cells could be verified by measuring their line centers on an FTS and summing the deviations of their line centers from the expected values at a variety of pressures. This quantity should be a minimum at the cell pressure. In practice, this can only be done for $H^{13}CN$, since $H^{13}CN$ lines have pressure shift slopes of different signs. The absorption lines of C_2H_2 and CO only increase in wavelength as the pressure increase, so their deviations from the measured values are dominated by the scatter in their measured line center values at low pressures.

We have verified the fill pressure of two $H^{13}CN$ cells, an example of which is shown in Figure 5. On an FTS, the input angle of the light systematically shifts the wavenumbers of the spectrum by a constant factor, on the order of a few parts in 10^7, known as the wavenumber correction factor. This effect is easily calibrated out by comparing the measured wavenumbers with standard measurements. Since the gas wavenumber standards vary depending on the pressure of the cell, we calculated the expected standards for the HCN wavenumbers at a variety of pressures and monitored the standard deviation in the wavenumber correction factor plots (top of Fig. 5) as a function of pressure. This scatter reaches a minimum at a pressure of 22.5 Torr (bottom of Fig. 5), which is just within the manufacturer's fill pressure uncertainty of 10%. Since the wavenumber correction factor is constant for the entire spectrum, once the fill pressure is known on a single cell, the measured wavenumber correction factor can be used to verify the fill pressure of the other gas cells by using the cells in series.

The wavelengths of the lines also depend on temperature, since an increase in temperature increases the gas pressure in the sealed cell. The temperature-dependance on the pressure shift slope is small, and has been outlined elsewhere,[10,21] but is summarized here for completeness. As the pressure rises, the collision frequency increases. In the fixed-volume of a gas cell, this temperature rise translates directly to an increase in the mean relative velocity of the molecules. The pressure shift slope $d\lambda/dP$ at temperature T is dependent upon the pressure shift slope $(d\lambda/dP)_m$ measured at T_m:

$$\left(\frac{d\lambda}{dP}\right)_T = \left(\frac{d\lambda}{dP}\right)_{T_m} \sqrt{\frac{T}{T_m}} \tag{4}$$

where both temperatures are in Kelvin. This change in the pressure shift slope translates to an apparent radial velocity shift:

$$\Delta v = c\frac{\Delta\lambda}{\lambda} = c\frac{P}{\lambda}\left(\left(\frac{d\lambda}{dP}\right)_T - \left(\frac{d\lambda}{dP}\right)_{T_m}\right) = c\frac{P}{\lambda}\left(\frac{d\lambda}{dP}\right)_{T_m}\sqrt{\frac{T}{T_m} - 1} \tag{5}$$

where c is the speed of light. This apparent velocity shift is largest for the CO cells, which have the largest pressures. Even for these cells, a one-degree deviation from the measured temperature translates to a velocity shift of at most 86 cm/s.

4. DISCUSSION

Uranium neon hollow cathode lamp provide a wider spectral coverage than the absorption cells we have tested, but the lamps are expected to age in the same manner as thorium-argon. As the lamp ages, the ever-increasing inner-diameter of the cathode will cause the uranium lines to illuminate the spectrograph in a slightly different manner than before. The HARPS spectrograph[25] has tried to mitigate this issue by using master lamps that are used infrequently.

The telecommunications gas cells avoid some of the issues with HCLs by utilizing single-mode fibers, which provide a more consistent illumination pattern over time. However, these cells are limited to a narrow wavelength range in the H-band. These cells will prove most useful on high-resolution spectrographs with a limited simultaneous bandpass, such as CRIRES.

Later this year, we will be working at CRIRES to produce a near-infrared atlas of uranium neon and thorium argon. This atlas will allow astronomers to make quick comparisons between the two sources between 1 and 5 μm at a resolution (R $\approx$ 100 000) that is typical of some of the echelle spectrographs currently under construction.

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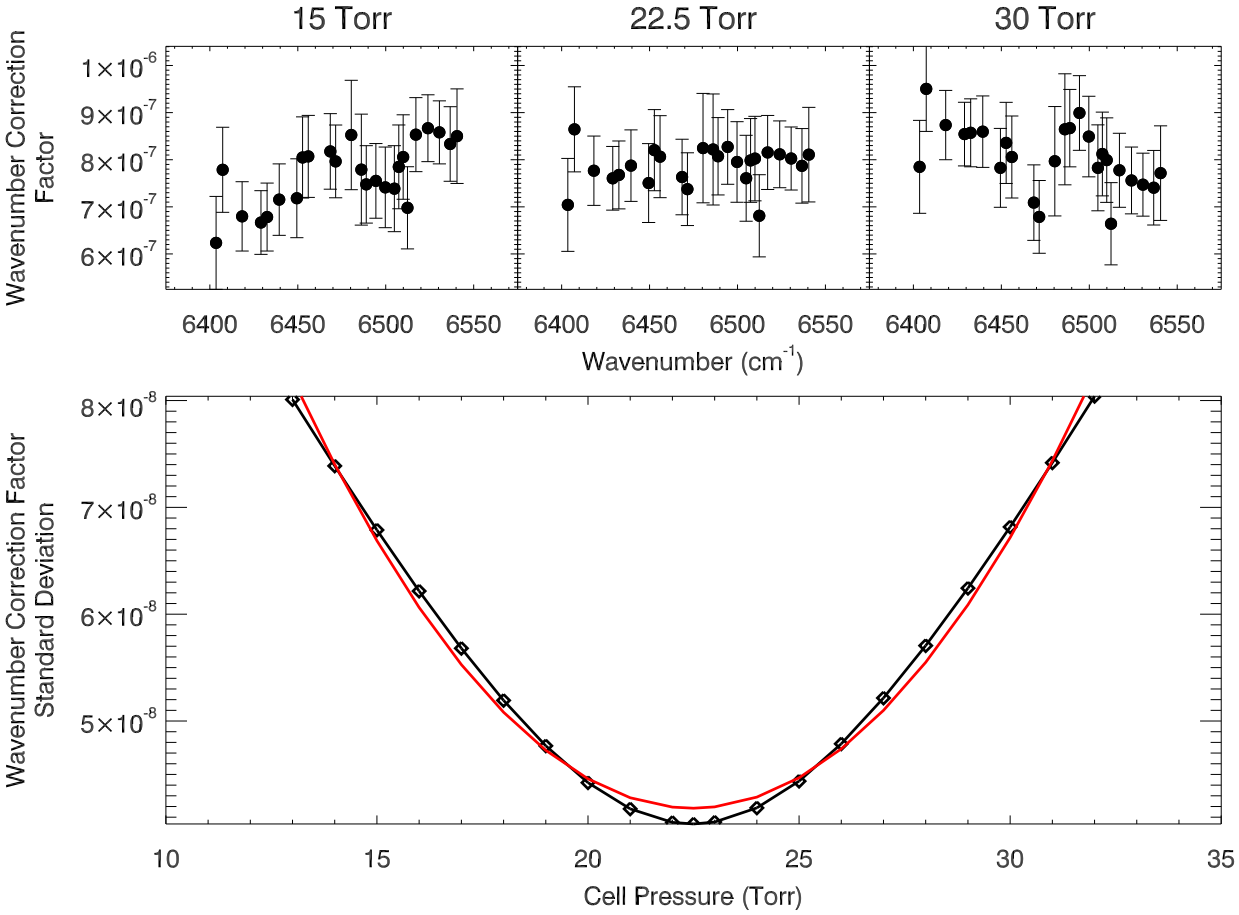

Figure 5. An example of the technique used to verify the cell pressure of the $H^{13}CN$ cells. The wavenumber correction factor uncertainty changes as different pressures are assumed. This technique cannot easily be used for the other telecommunications gas cells, because the pressure-shift slopes are all positive, so the change in the wavenumber correction factor uncertainty is very small.

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In the third quarter of 2012, we will test the telecommunications gas cells on-sky at the Very Large Telescope (VLT)/CRIRES on radial velocity standard stars. These tests will be useful for providing a practical estimate of the radial velocity precision that can be obtained with these cells.

5. CONCLUSIONS

We have presented our current knowledge of two near-infrared calibration sources. Uranium neon provides excellent spectral coverage over the whole of the near-infrared, but line blending remains a technical challenge to accurate wavelength calibration of astronomical spectrographs. Four gas cells used as wavelength references by the telecommunications industry — containing C_2H_2, $H^{13}CN$, ^{12}CO, and ^{13}CO, respectively — provide deep absorption lines over the H band, especially C_2H_2 and $H^{13}CN$. We will construct an atlas of these HCL sources and test the gas cells with astronomical radial velocity standard stars this fall at VLT/CRIRES.

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