# Calibration Sources for CRIRES

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**We report on our efforts to provide high accuracy wavelength calibration to the scientific observations with the Cryogenic High-Resolution IR Echelle Spectrograph (CRIRES), ESO's new high resolution (R~100,000) infrared (IR) spectrograph at the VLT. In order to provide reliable and accurate wavelength standards for CRIRES the European Southern Observatory (ESO), in collaboration with the the Space Telescope European Co-ordinating Facility (ST-ECF) and the National Institute of Standards and Technology (NIST), embarked on a project to establish Th-Ar wavelength standards in the 900 nm - 5000 nm operating range of CRIRES. Based on current findings we conclude that Th-Ar hollow cathode lamps hold the promise of becoming a standard source for wavelength calibration for near IR astronomy, providing a high density of sharp well-characterized emission lines with the ease and efficiency of operation of a commercial discharge lamp. In addition, and for use at wavelengths larger than 2200 nm, we have establish a gas cell filled with $N_2O$ as a calibration source based on existing data from NIST. Both sources were extensively tested during CRIRES commissioning runs and both will be used for routine operations of the instrument. With the availability of reliable and well characterized sources wavelength calibration, the near IR will become very similar to the UV-visible region, and it will become possible to support high accuracy absolute wavelength calibration without having to rely on atmospheric features.**

## Wavelength Calibration in the near-IR

Traditionally, astronomical spectroscopy in the near infra-red (IR) has relied on atmospheric features of the night sky for wavelength calibration (Rousselot et al. 2000, A&A, 354, 1134). The lines from rotation-vibration levels of the hydroxyl radical OH (Meinel bands), which account for the night time OH airglow emission, are routinely used since they are very numerous, cover a wide wavelength range, and have been studied in detail at high resolution (Abrams et al. 1994, ApJS 93, 351). This approach takes advantage of the fact that the night sky lines are imprinted on any spectrum of an astronomical target. While this is a significant complication for scientific observations, it reduces the need for dedicated calibration exposures. The main limitations of the method are in the number of lines available in a given wavelength range and at a given resolution. Experience with ESO's Cryogenic High-Resolution IR Echelle Spectrometer (CRIRES) during commissioning shows that at high resolution the intensity of the OH night lines will be too low to be used for calibration purposes in many cases.

On the other hand, the use of calibration sources such as lamps or gas cells is limited, because these sources have not been extensively measured in the near-IR and hence only a limited number of wavelength standards are available. Although more extensive measurements have recently been made of the noble gases in this region (Sansonetti et al. 2002, Phys Scr T100, 120; 2004, J. Res. NIST, 109, 371), the density and distribution of their spectra are inadequate for high-resolution spectroscopy. Thus the situation in the near-IR is in pronounced contrast to the UV and visible regions, where wavelength calibration is usually made using calibration spectra provided by a standard lamp and where the study of the night sky lines is left to dedicated observations (Hanuschik 2003, A&A, 407, 1157).

European Southern Observatory (ESO), the Space Telescope European Co-ordinating Facility (ST-ECF), and the United States National Institute of Standards and Technology (NIST) are collaborating to establish the Th-Ar hollow cathode lamp as a standard for the calibration of VLT (Very Large Telescope) spectrographs in the near infrared (IR).

## Wavelength Calibration Sources for CRIRES

Originally, the concept for **CRIRES** wavelength calibration was based on the use of features provided by the night sky. In the course of CRIRES commissioning we realized that for most of the CRIRES wavelength range only few and faint features are evident. These were obviously not appropriate for high accuracy calibration purposes. We therefore intensified efforts to establish external source wavelength standards in the near-IR for use with CRIRES. Available sources are discharge lamps and gas cells. Based on considerations of scientific potential, practicability and availability we selected Th-Ar hollow cathode lamps and $N_2O$ gas cells as prime candidates.

### Th-Ar Hollow cathode lamps

Modern commercial hollow cathode lamps (HCLs) are sealed-off glass tubes that contain a metal cathode, a metal anode and a fill gas at a defined pressure. The lamp is operated by applying a voltage of a few hundred volts across cathode and anode. As a result, a discharge is formed in the low pressure (few hundred Pa) fill gas and positive ions of the plasma are accelerated towards the cathode where they release matter through sputtering. As a result a HCL emits a rich spectrum of narrow emission lines from both the gas and metal atoms and ions in the plasma. The Th spectrum was studied from 278 nm to about 1000 nm at high resolution more than 20 years ago by Palmer & Engleman (1983, LANL Report LA-9615). Its emission lines are very narrow and the spectrum is rich over a wide wavelength range. In nature Th has only one isotope, $^{232}$Th, which has zero nuclear spin. Thus the use of Th for calibration lines avoids complex and asymmetric line profiles attributable to isotopic or hyperfine structure.

Two valuable studies of the Th-Ar spectrum in the near IR have recently been published, but neither is directly applicable to the operation of CRIRES:

- Hinkle et al. (2001, PASP, 113, 548) produced an atlas of the Th-Ar spectrum covering selected regions in the range 1000 nm to 2500 nm. They established wavelength standards using the McMath 1-m laboratory Fourier Transform Spectrometer (FTS) at the US National Solar Observatory at Kitt Peak. However, the density of lines provided by the FTS spectrum was insufficient in many regions for deriving dispersion solutions. They augmented their atlas by using blocking filters to observe selected regions with the Phoenix grating spectrograph at Kitt Peak. As a result their list of about 500 lines contains significant gaps in wavelength coverage.

- More recently, a fundamental analysis of the Th-Ar spectrum was provided by Engleman, Hinkle & Wallace (2003, JQSRT, 78, 1). Their list contains more than 5000 lines derived from observations of a Th-Ar source with the McMath FTS. They used a water-cooled demountable hollow cathode lamp operated at 320 mA with a continuous flow of argon at a pressure of 290 Pa (2.2 Torr). Such a lamp produces a very rich Th spectrum, but it is very different from low current commercially available lamps and is not well-suited for operation at an astronomical facility. Although the spectrum from the high current lamp is significantly different from commercial Th-Ar lamps, the line list is highly valuable for identification of the lines in low current spectra and we are trying to verify whether some of the fainter lines can also be used for CRIRES operations.

### Gas Cells

The CRIRES gas cells consist of a sealed tube of about 18 cm length which contains $N_2O$ (nitrous oxide or "laughing gas") at a well defined pressure. During operations we use a halogen lamp as background illumination. The lines from the transition of the gas appear in absorption superimposed on the bright continuum of the lamp.

$N_2O$ was chosen for practical reasons and it is a primary calibration molecule from Heterodyne frequency measurements at NIST (Maki & Wells, http://physics.nist.gov/PhysRefData/wavenum/html/spect.html).

Hence a large number of lines of its fundamental mode have been established covering the range 523 – 2845 cm $^{-1}$ (1912 – 3515 nm). In addition a large data set on $N_2O$ has been measured with the MARK IV FTS at NASA's Jet Propulsion Laboratory (JPL) (http://mark4sun.jpl.nasa.gov) and $N_2O$ http://mark4sun.jpl.nasa.gov/n2o.html) is also included in the HITRAN 2004 (http://cfa-www.harvard.edu/hitran ) database based on a list by R.A. Toth. Model spectra can be calculated as a function of pressure and temperature using a spectral synthesis code (FASCODE in a PCLNWIN/IDL wrapper). The use of gas cells was originally foreseen as a somewhat specialized application in e.g. radial velocity studies. During commissioning we have established that they can also be used as a standard source for routine wavelength calibration (Fig. 3).

## Laboratory Work at NIST

Spectra of the Th-Ar lamps operated at 20 mA were recorded on the NIST 2-m FTS. The FTS (Nave, Sansonetti, & Griesmann 1997, Fourier Transform Spectroscopy: Methods and Applications. OSA Technical Digest Series, 3, 38) was fitted with a $CaF_2$ beam splitter, silver coated mirrors, and InSb detectors. To obtain a good signal-to-noise ratio many interferograms were co-added for each spectrum, corresponding to acquisition times of up to 20 h. Radiometric calibration was achieved using a calibrated tungsten ribbon lamp. We anticipate that the final wave number values for strong narrow lines will be accurate to 0.001 cm$^{-1}$, but the deviation for weak and broad lines may be substantially greater. As a result of this laboratory work a total of about 2500 lines in the range 900 nm to 4800 nm is available for CRIRES wavelength calibration. In general the line density drops significantly towards longer wavelengths. The overall intensity is a function of operating current as is the intensity of the continuum from the hot cathode beyond 2500 nm (Fig. 1). Similarly the relative intensity of Th and Ar lines is strongly dependent on the operating current. For a detailed description of the results we refer to Kerber et al. (2006, 2005 HST Calibration Workshop, A. Koekemoer, P. Goudfrooij, and L. Dressel, eds., p. 318, 2007, The Future of Photometric, Spectrophotometric and Polarimetric Standardization, ASP Conf. Ser. Ed. C. Sterken, in press).

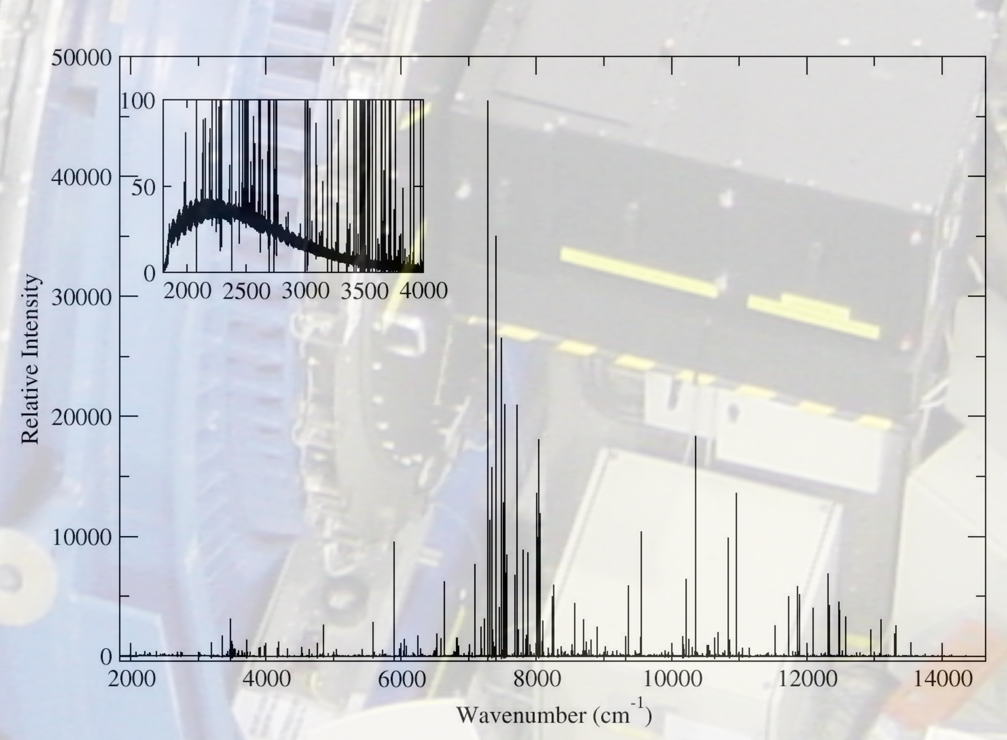


*Figure 1: Overview spectrum of a Th-Ar lamp. Wavelength range is 715 nm to 5000 nm (14000 cm$^{-1}$ to 2000 cm$^{-1}$). The line intensity is given in arbitrary units. The inset shows that longwards of 2500 nm (<4000 cm$^{-1}$), thermal emission from the hot cathode produces a continuum that underlies the pure emission line spectrum.*

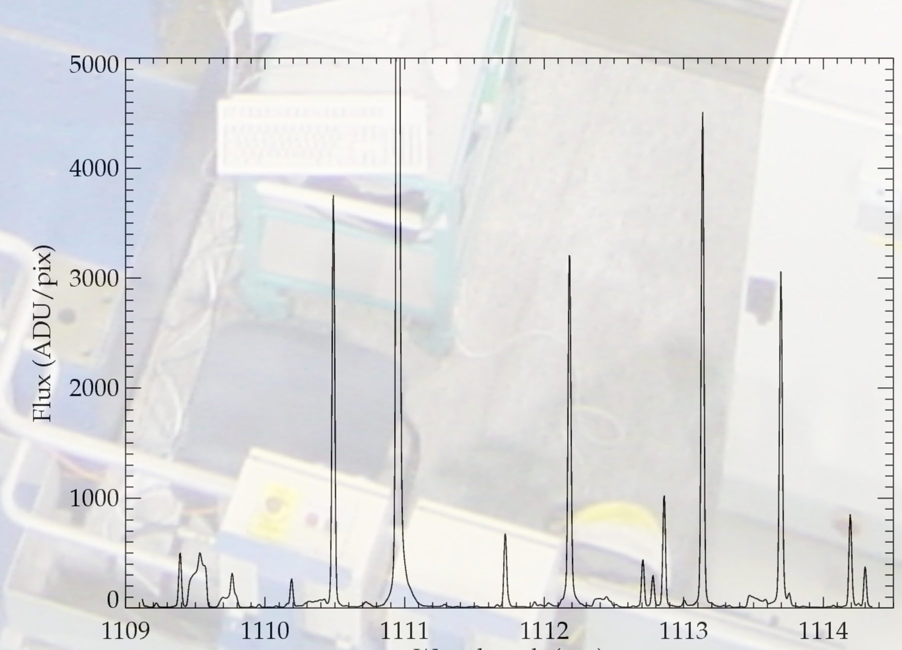


*Figure 2: CRIRES observations of the Th-Ar lamp.*

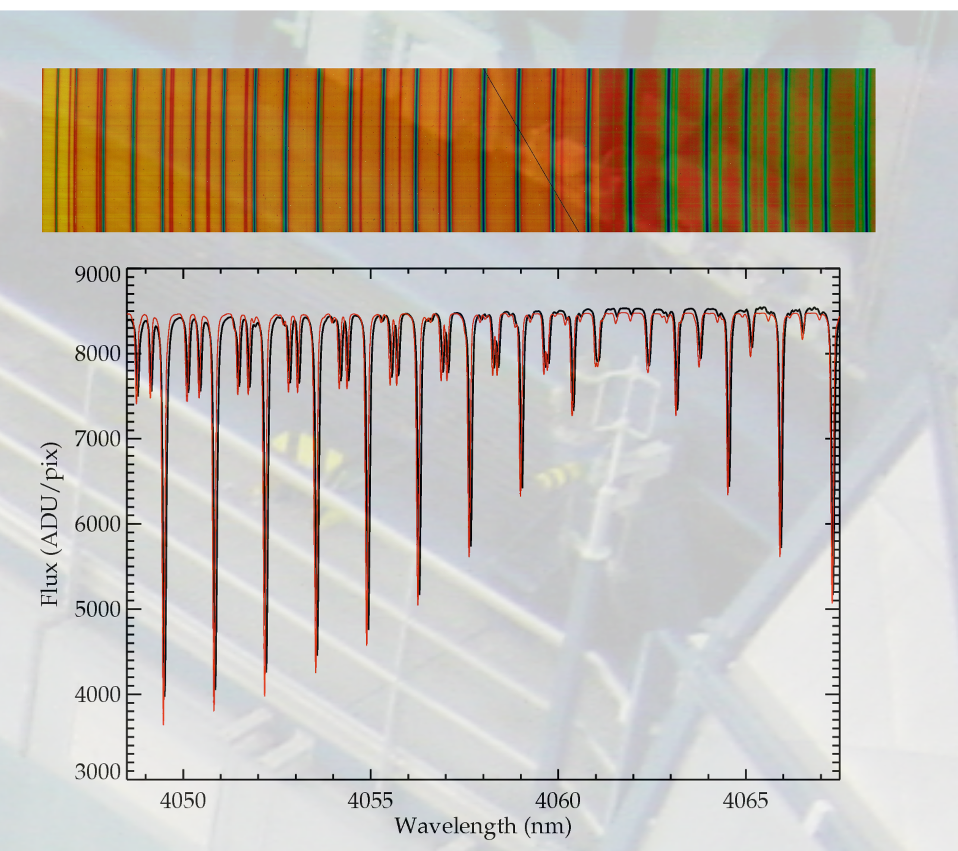


*Figure 3: Raw spectra of an $N_2O$ gas cell recorded during commissioning III (October 2006). The spectrum, taken with black body illumination and a 2 s exposure time, was flatfield corrected and smoothed to a resolution of 65.000 using a preliminary wavelength solution. Upper panel: sample 2-D Spectrum on CRIRES detector array (gaps between electronically removed). Lower panel: 1-D representation of the spectrum overplotted in red with the HITRAN/FASCODE spectrum of $N_2O$ for a 13 cm gas cell at a pressure of 50mb.*

## Results from CRIRES Commissioning and Current Status

- During the course of CRIRES commissioning we were able to develop a set-up that guarantees an easy and efficient use of both the Th-Ar lamp and the $N_2O$ gas cell as calibration source (Figs 2 & 3).

- CRIRES is a sensitive grating spectrograph and is able to observe considerably more Th-Ar lines than have been established as wavelength standards with the NIST FTS. We plan to take advantage of this sensitivity and hope to establish additional wavelength standards through use of available literature data (work in progress) and possibly further laboratory measurements.

- In the current set-up we plan to use Th-Ar as the default calibration source in the range 950-2200 nm. For wavelengths between 2200 and 4100 nm the $N_2O$ gas cell will be used as default while the Th-Ar will serve as an alternative when applicable. At wavelengths beyond 4100 nm both sources have a sparse spectrum and atmospheric features currently remain an option.

- For effective use as calibration source, the spectrum of the CRIRES gas cell needs to be properly characterized. The intensity and width of the lines are dependent on pressure and temperature and an optimal choice of fill gas pressure will be based on measurements using ESO's FTS.

- The first overtone transitions of $N_2O$ offer an interesting option for wavelength calibration at shorter wavelengths for specific applications.

- We are currently investigating the possible use of OCS (carbonyl sulfide), another NIST standard – as calibrator either in a separate gas cell or in a mixture with $N_2O$.

## SUMMARY

The joint efforts of ESO, NIST and ST-ECF to establish wavelength standards in the near-IR for Th-Ar have resulted in a list of about 2500 lines in the wavelength range 900 - 5000 nm. In addition we have used published data from NIST and JPL to investigate the use of $N_2O$ gas cells as calibration source. Both Th-Ar hollow cathode lamps and $N_2O$ gas cells have been successfully tested during commissioning and both are now available for routine use on CRIRES.

A number of steps are planned to further enhance the value of both sources. In particular we have a dedicated effort to make more Th-Ar lines available for use in wavelength calibration. For $N_2O$ we will characterize the spectrum of the CRIRES gas cell as a function of temperature and pressure with the ESO FTS and we are investigating additional fill gases.

With this development, wavelength calibration in the near IR will become very similar to the UV-visible region. It will be possible to support high accuracy absolute wavelength calibration without having to rely on atmospheric features. This is an essential step towards supporting the fundamental studies planned for the next generation of extremely large telescopes.

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