We report on our efforts to provide high wavelength accuracy calibration to the scientific observations with the cryogenic high-resolution IR echelle spectrograph CRIRES, its new hollow-cathode array (HRCA) spectrally sampled at the VLT. In order to provide reliable and accurate wavelength standards for CRIRES the European Southern Observatory (ESO), in collaboration with the the ESO Telescope European Coordinating Facility (ST-ECF) and the National Institute of Standards and Technology (NIST), embarked on a project to establish Th-Ar hollow cathode standards in the near IR astronomy, providing a high density of sharp well-characterized emission lines with the ease and efficiency of operation of commercial discharge lamps. In addition, and for use at wavelengths larger than 2200 nm, we have developed a gas cell filled with N2O 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 infrared (IR) has relied on atmospheric features of the night sky for wavelength calibration (Rosenbusch et al. 2000, A&A, 354, L13). The lines from rotation–vibration levels of the hydrogen and carbon dioxide bands, which are emitted from the auroral region, are routinely used since they are easy to access, cover a wide wavelength range, and have been studied in detail at high altitudes (Aalto et al. 1994, ApJ, 434, 335). This approach takes advantage of the fact that the night sky lines are independent on any spectrum of any atmospheric target.

With this there is a significant complication for scientific observations, it reduces the need for the data and calibration observations. The measurement methodology being used is the number of available lines in a given wavelength range or at a given resolution. Experience with ESO’s Cryogenic High-Resolution IR Echelle Spectrometer (CRIRES) during commissioning shows that at high resolution the number of the OH night lines will be too low to use for calibration purposes in the near IR.

On the other hand, the use of calibration sources such as lamps or gas cells is limited by the availability of a limited number of wavelengths standards, which are usually provided in the form of high-quality synthetic spectra. The availability of these standards is limited, and there are inadequate for high-resolution spectroscopy.

The situation in the near-IR is prominent contrast to the UV and visible regions, where wavelength calibration is usually made using telluric spectra provided by a standard lamp and the measured line positions in line to line to line is linked to dedicated observations (Rosenbusch 2003, A&A, 407, L175).

European Southern Observatory (ESO), the Space Telescope European Coordinating Facility (ST-ECF) and the National Institute of Standards and Technology (NIST) are collaborating to establish the Th-Ar hollow-cathode lamp standards for the calibration of VLTI (VLT 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 telluric lines. In the course of CRIRES commissioning we realized that for most of the CRIRES wavelength range only few and faint features are evident. Th-Ar gas cells as prime candidates.

Th-Ar hollow-cathode lamps

Modern commercial hollow cathode lamps (HCLs) are sealed-off glass tubes that contains a metal cathode, a metal anode and a fill gas a defined composition. Although the spectrum from the high current lamp produces a rich output spectrum and are suitable for wavelength calibration in the near infrared.

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, 544) produced an atlas of the Th-Ar spectrum covering selected regions in the range 3900–22000 nm. They established wavelength standards using the McMath 1-meter solar Fraunhofer lines Spectrophotometer (FTS) at NIST National Solar Observatory at Kitt Peak. However, the density of lines provided by the FTS spectrum was not sufficient for deriving dispersion solutions. They augmented their atlas by using blocking filters to observe selected regions with the Photospheric Scintillating Spectrograph at Kitt Peak. As a result, a list of about 500 lines contains significant gaps in wavelength coverage.

More recently, a fundamental development of the Th-Ar spectrum was provided by Engelschoff, Hinkle & Welch (2003, SPIE, 5178, 715). This work contains more than 5000 lines derived from observations of Th-Ar source with the McMath FTS. They used a source-averaged denser hollow-cathode lamp operated at 320 mA with a continuous flow of argon at a pressure of 0.85 Torr. Such a lamp produces a very wide wavelength spectrum, but it is very different from low current commercially available lamps and is not well suited for operation at an astronomical observatory.

Although the Th-Ar hollow-cathode lamp is significantly different from commercial Th-Ar lamps, the line list is highly valuable for identifying spectral lines and we are verifying whether some of the far-red lines also can be used for CRIRES operations.

Th-Ar gas cells contain a sealed tube of about 10 mm length which contains the metal (usually called “filling gas”) at a well-defined pressure. During operations we use a halogen lamp as background illumination. The lines from the tranmission of the gas cell in the range >2200 nm have been measured on the bight continuum of the lamp.

The Th-Ar content in the gas cell is strongly dependent on the primary production and it is a primary calibration molecule from Herzberg's baseline measurement at NIST (Hinkle & Wallace 2003, JQSRT, 78, 1). Their list of about 500 lines contains significant gaps in wavelength.

Hence a large number of lines of its fundamental mode have been established covering the range 810–2400 nm. ThisTh-Ar gas cell is placed on the NIST FTS in NIST Vacuum Propulsion Laboratory (http://physrefdata.nist.gov/) and NIST’s 2-m McMath Solar Telescope. It is also tabulated in the HITECH-2000 (G. Engelschoff, 1999) 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 PC/Windows/SDR) software. The use of gas cells was originally designed as a versatile spectral application in e.g. radial velocity studies. During commissioning we have realized that they can also be used as a standard source for 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 (NIST, Sanborn, & Greenfield 1991, Intelligent Spectroscopy Methodology and Applications. OSA Technical Digest, 1, 30) was fitted with a CaF2 beam splitter, fiber coupled, imaging, and field detector. To obtain a good signal-to-noise ratio many interferograms were recorded for each spectrum, corresponding to acquisition times of up to 20 h. Radiometric calibration was achieved using a calibrated tungsten ribbon lamp. We notice that the final mean number values for scanning lines will be accurate to 0.01 nm, but the deviation for weak and broad lines may be substantially greater. As a result of this calibration a list of about 2000 lines in the range 900 nm to 4000 nm is available for CRIRES wavelength calibration. In general the list already shows significantly longer wavelength. The overall intensity is a function of temperature and pressure. The overall intensity is a function of temperature and pressure.

During the course of commissioning III (October 2006), the FTS (Nave, 2003, JQSRT, 78, 1) was fitted with a CaF2 beam splitter, fiber coupled, imaging, and field detector. To obtain a good signal-to-noise ratio many interferograms were recorded for each spectrum, corresponding to acquisition times of up to 20 h. Radiometric calibration was achieved using a calibrated tungsten ribbon lamp. We notice that the final mean number values for scanning lines will be accurate to 0.01 nm, but the deviation for weak and broad lines may be substantially greater. As a result of this calibration a list of about 2000 lines in the range 900 nm to 4000 nm is available for CRIRES wavelength calibration. In general the list already shows significantly longer wavelength. The overall intensity is a function of temperature and pressure. The overall intensity is a function of temperature and pressure. The overall intensity is a function of temperature and pressure.

We are currently investigating the possible use of OCS (carbon disulfide), another noble gas – Th-Ar as calibration either in a separate gas cell and/or in a mixture with N2.

Results from CRIRES Commissioning and Current Status

• During the course of CRIRES commissioning we were able to develop a survey that guarantees an easy and efficient use of both the Th-Ar lamp and the N2O gas cell as source calibration (Fig 2).

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

• In the current survey we plan to use Th-Ar as the default calibration source in the range 900-2000 nm. For wavelengths between 2300 and 4800 nm the N2O gas cell will be used as default while the Th-Ar will serve as an alternative when appropriate. At wavelengths beyond 4800 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 empirical validation of N2O offer an interesting option for wavelength calibration at chromatic wavelengths for specific applications.

• We are currently investigating the possible use of OCS (carbon disulfide), another noble gas – Th-Ar as calibration either in a separate gas cell and/or in a mixture with N2.

SUMMARY

The joint efforts of ESO, NIST and ST-ECF established wavelength standards in the near-IR for Th-Ar to have resulted in a list of about 2000 lines in the wavelength range 900 – 4000 nm. In addition we have used published data from NIST and JPL to investigate the use of N2O gas cell calibration source. Both Th-Ar hollow-cathode lamps and N2O gas cells have been extensively used during commissioning and are now available for routine use on CRIRES.

A number of steps are planned to further enhance the value of both sources. In particular a development of a dedicated cryogenic versions of the Th-Ar gas cell will be presented at CRIRES commissioning, and both are now available for routine use on CRIRES.