Calibration Sources for the Near-IR Arm of X-shooter

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We have studied the properties of wavelength calibration sources for the near-IR arm of X-shooter. In a novel approach we are combining laboratory measurements from a Fourier Transform Spectrometer (FTS), and literature data, with simulated data derived from a physical model of X-shooter. The sources studied are pen ray lamps filled with the noble gases Ne, Ar, Kr, and Xe and Th-Ar hollow cathode lamps. As a product we provide a quantitative order by order analysis of the expected properties of the calibration lamps during X-shooter operations. Based on these we give recommendations for the selection of the best combination of lamps. The combination of laboratory measurements and instrument modelling provides a powerful tool for future instrument development.

Intoduction to X-shooter

X-shooter is a single-target spectrograph for the Cassegrain focus of one of the VLT UTs, covering in a single exposure the spectral range from the *UV*- to the *K*-band (320–2500 nm). It is designed to maximise the sensitivity in this spectral range by splitting the incoming light into three arms – ultraviolet blue, visible and near-infrared (UVB, VIS and NIR) – with optimised optics, coatings, dispersive elements and detectors. X-shooter will be a unique instrument on 8-m-class telescopes in that it is capable of recording – over such a large wavelength range – the spectrum of an astronomical target in a single exposure. It operates at intermediate resolutions (R = 4000–14000, depending on wavelength and slit width) sufficient to address quantitatively a vast number of astrophysical applications, while working in a background-limited signal-to-noise regime in regions of the spectrum free from strong atmospheric emission and absorption lines. The instrument is currently undergoing subsystem assembly and commissioning is scheduled for 2008.

Wavelength calibration during X-shooter operations

X-shooter has a dedicated calibration unit providing light for flat fielding and wavelength calibration across the entire operating range of the instrument. For NIR wavelength calibration, the light of up to four pen ray lamps (Ne, Ar, Kr, Xe) is superimposed in the integrating sphere and the combined spectrum is fed to the spectrograph. The four pen ray lamps will be operated as a single source, that is all lamps, although using separate power supply units (PSUs), will be burning simultaneously and for the same length of time. Hence, the intrinsically different intensity levels of the lamps need to be balanced by the positioning of the lamps inside the integrating sphere and by shielding cylinders mounted around the lamps. We have studied the properties of pen ray lamps with a noble fill gas of Ne, Ar, Kr or Xe and Th-Ar hollow cathode lamps in order to provide a basis for the selection of the best lamp combination.

Wavelength calibration sources for X-shooter

In order to fully realise the scientific potential of X-shooter, excellent wavelength calibration across all three arms is essential. For UVB and VIS, Th-Ar hollow cathode lamps have been chosen as calibration sources following the successful operations of such lamps in e.g. FEROS, FLAMES, HARPS and UVES. For the NIR arm the situation is less obvious and we decided to conduct a dedicated programme to select the best combination of calibration sources for this wavelength region, which traditionally has relied on atmospheric features for wavelength calibration. Recently, ESO has gained significant experience with NIR wavelength standards in a collaboration with the US National Institute of Standards and Technology (NIST) as part of the CRIRES project (Kerber et al. 2007). Currently, there is no comprehensive database of emission line spectra of commercially available light sources. Based on experience, a combination of gas discharge lamps (Ne, Ar, Kr, Xe pen ray lamps) was envisaged. In addition we looked into the possibility of utilising a Th-Ar hollow cathode lamp – the calibration source for X-shooter UVB and VIS arms – also for the NIR arm.

Pen ray lamps

These lamps are called ‘Pencil’ lamps because of their size and shape. They are made of double bore quartz tubing with two electrodes at one end sealed into a handle. These lamps produce narrow, intense lines from the excitation of various rare gases and metal vapours. These commercial products are widely used for wavelength calibration of spectroscopic instruments such as monochromators, spectrographs, and spectral radiometers e.g. in industrial and chemical analysis applications. As input for our analysis, we used the line data available in the literature: Ne (Sansonetti, Blackwell and Saloman 2004); Ar (Whaling et al. 2002); Kr (Sansonetti and Greene 2007); and Xe (Saloman 2004).

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 Pascal) fill gas and positive ions of the plasma are accelerated towards the cathode where they release matter through sputtering. As a result an 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 more than 20 years ago in the range from 278 nm to about 1000 nm at high resolution by Palmer and Engleman (1983). 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. Th-Ar HCLs are widely used for wavelength calibration of high-resolution spectrographs in the visual wavelength range, including many examples at ESO such as FEROS, FLAMES, HARPS, and UVES. A detailed account of the properties, design and operations of HCLs is given in Kerber et al. (2007).

Two valuable studies (Hinkle et al. 2001; Engleman et al. 2003) of the Th-Ar spectrum in the near IR have recently been published, but neither is directly applicable to the operation of X-shooter. The spectrum of low current Th-Ar HCLs has been studied extensively at high spectral resolution by a collaboration of ESO and NIST for the ESO CRIRES spectrograph. X-shooter directly benefits from this experience.

Figure 1: The Fourier Transform Spectrometer in ESO's laboratory.

Laboratory measurements at ESO

ESO operates a commercial Fourier Transform Spectrometer (FTS) (model Thermo 5700) in its laboratory (Figure 1). The spectrometer is equipped with an external port that allows one to feed the light from an external light source to the FTS for analysis. We have built a permanent set-up for the external feed which replicates part of the optical train of the FTS.

Wavelength range and resolution were chosen to match the X-shooter NIR arm. We recorded several spectra of all lamps, varying both current and exposure time. Long exposure times are essential in order to reach a reasonable signal-to-noise ratio. Spectra of the four pen ray lamps are shown in Figure 2.

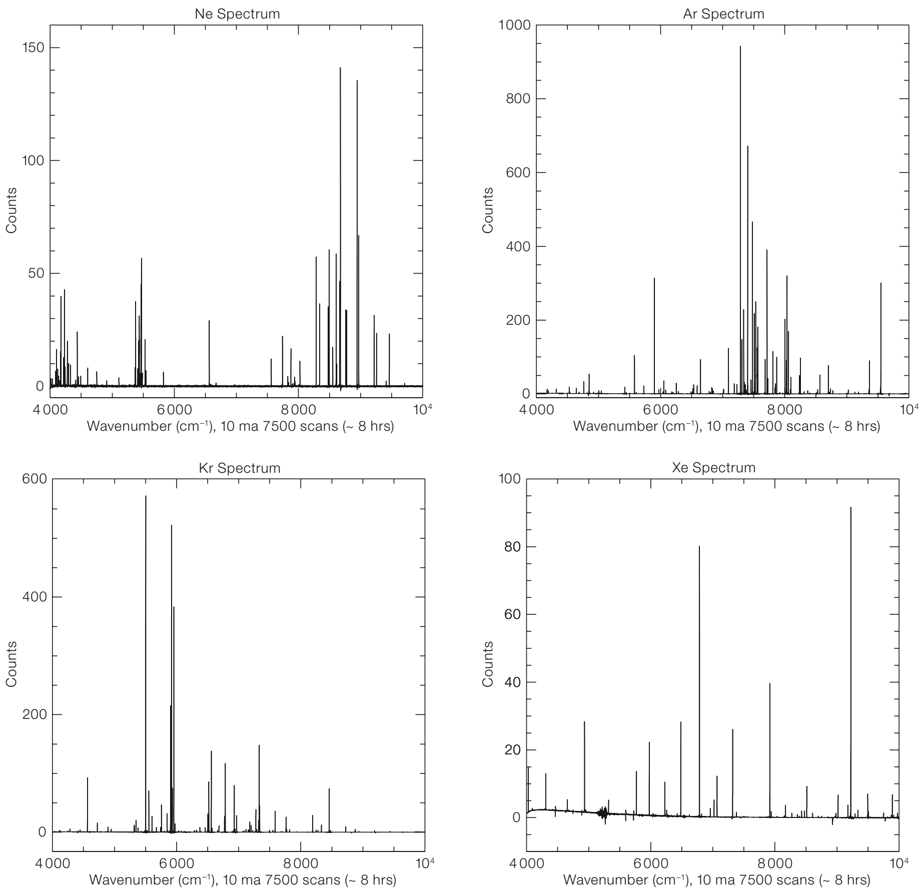

Figure 2: Spectra of the pen ray lamps filled with Ne, Ar, Kr, Xe observed at X-shooter spectral resolution.

Physical modelling and simulated data

The Calibration and Modelling Support Group in the ESO Instrumentation Division uses advanced modelling techniques to describe the performance of an instrument. In this we replace the standard empirical method of wavelength calibration (polynomial fitting) by using our physical understanding of the instrument as it was employed in the optical design. During the testing of the instrument the model will be optimised and then describes the instrument as built. This configuration is later used to support the operations of the science data reduction pipeline. During the integration phase of X-shooter, the physical model uses the design parameters. For the purposes of this study it was important not only to know where a photon of a given wavelength arrives on the detector, but also the spectrograph throughput (which we combine with the spectral line intensity) at that wavelength. This is achieved via empirical functions that describe the quantum efficiency of the detectors and the throughput of the dichroics at each wavelength. In addition we include the grating blaze efficiency in the simulation.

We use a Monte-Carlo approach to simulate the counts expected on the detector array during an exposure. In this way 2D simulated data containing many photons are produced by multiple calls of the physical model code. In the current project, we take the 2D simulated data (see Figure 3) for each lamp and extract a 1D spectrum along the loci traced on the detector array by photons arriving at the centre of the entrance slit for all spectral orders. As a result we have, for each lamp and each order, a 1D extracted spectrum. Figure 4 shows a sample 1D spectrum (order #20 of the NIR arm). Full details and an atlas of all X-shooter NIR orders will be available in a comprehensive report (Kerber et al., in preparation).

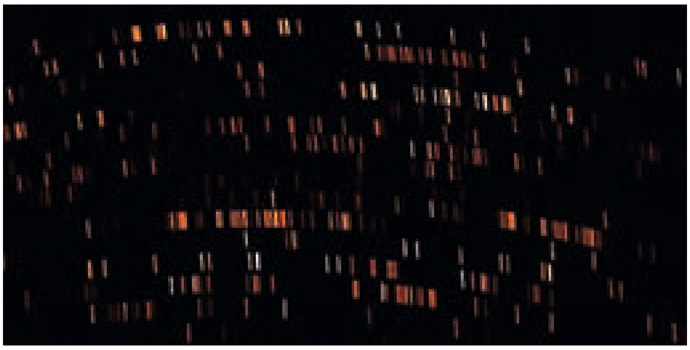

Figure 3: Simulated 2D spectrum of Ne as observed with the X-shooter NIR arm.

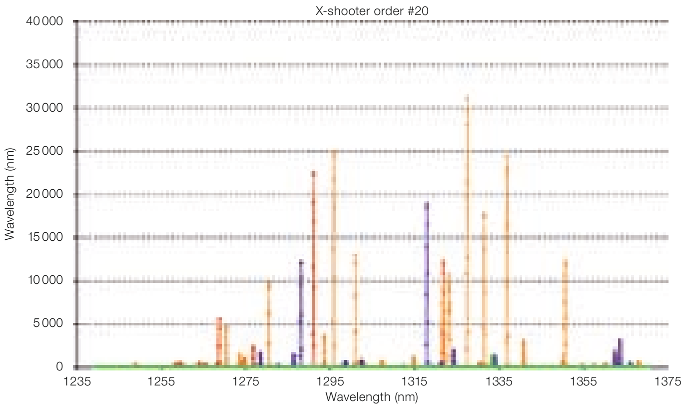

Figure 4: Simulated 1D spectrum of X-shooter order #20 as it will be provided by the integrating sphere in the calibration unit. The lines from different lamps are colour-coded.

Results

The following results have been derived from our measurements for the X-shooter NIR arm:
– The spectra of pen ray lamps filled with Ne, Ar, Kr, and Xe have been measured at a spectral resolution equivalent to the X-shooter NIR, as well as at higher and lower resolution to assess blending of lines.
– The relative intensities of the lamps have been derived as an integral of the line fluxes. The intensities of the Ne, Ar and Kr lamps are within a factor of three of each other while Xe is another three times fainter than the next faintest source.
– No good calibration spectrum can be created from any combination of two lamps.
– A combination of Ne, Ar and Kr provides a suitable spectrum for X-shooter calibration in the NIR. It meets the requirement of 10 lines per order for all but two orders and approaches the goal of 30 lines per order for many orders. We therefore recommend this combination as a baseline for implementation in the calibration unit.
– The addition of Xe will only bring a small improvement in the number of lines and coverage. Since Xe is the faintest source, the feasibility and usefulness of its addition needs to be assessed during laboratory integration and testing.
– The region between 1880 and 2015 nm (orders 13 and 14) is almost devoid of lines, leaving no easy option to remedy the situation. For a dispersion solution based on an empirical polynomial fit, this could be a difficult situation. Since X-shooter will use a physical model to drive the wavelength calibration in the pipeline, we don't expect any significant negative impact on the accuracy of calibrations.
– The spectrum from a Th-Ar HCL offers a less favourable distribution of lines across the NIR spectral range. At the resolution of X-shooter, many of the faint Th lines in its rich spectrum are blended, thus rendering them unusable for calibration purposes.

The results provided need to be verified in detail during testing and commissioning of X-shooter, but they will also help to optimise and speed up the laboratory tests by providing quantitative predictions on the performance of the calibration lamps. This also has the benefit of reducing the pressure on the very busy testing and commissioning phases.

For future instrument developments, our new approach offers the opportunity to estimate and optimise the performance of a calibration system for an instrument already in the design phase.

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