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Performance of the FOS and GHRS Pt/(Cr)-Ne Hollow-cathode Lamps after their Return from Space and Comparison with Archival Data

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Abstract. The Space Telescope European Co-ordinating Facility (ST-ECF) and National Institute of Standards and Technology (NIST) are collaborating to study hollow cathode calibration lamps as used onboard the Hubble Space Telescope (HST).

As part of the STIS Calibration Enhancement (STIS-CE) Project we are trying to improve our understanding of the performance of hollow cathode lamps and the physical processes involved in their long term operation. The original flight lamps from the Faint Object Spectrograph (FOS) and the Goddard High Resolution Spectrograph (GHRS) are the only lamps that have ever been returned to Earth after extended operation in space. We have taken spectra of all four lamps using NIST's 10.7-m normal-incidence spectrograph and Fourier transform spectrometer (FTS) optimized for use in the ultraviolet (UV). These spectra, together with spectra archived from six years of on-orbit operations and pre-launch spectra, provide a unique data set - covering a period of about 20 years - for studying aging effects in these lamps.

Our findings represent important lessons for the choice and design of calibration sources and their operation in future UV and optical spectrographs in space.

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1. Introduction

The two lamps flown on the GHRs and on the FOS are the only calibration lamps ever returned from space after extended use in orbit. All four lamps had been retired to exhibits at museums. In the case of the GHRs the instrument had been disassembled after return and the lamps were on display at the Fiske Planetarium in Boulder, Colorado. The FOS lamps were still inside the instrument which is on display at the National Air and Space Museum in Washington, DC. Courtesy of the HST project and both museums, we were able to obtain all lamps on loan. In the case of the FOS this required us to actually open up the FOS and extract the two lamps in a delicate operation (Kerber & Wood 2004).

The measurements we obtained yielded the only spectra of calibration lamps after return from space. Combined with pre-launch spectra recorded during ground testing in 1984 and the extensive collection of spectra obtained during the 6.5 years of orbital operation (Apr 1990 - Jan 1997) we have assembled a 20 year history of the spectral output of these lamps. This constitutes a unique database to study time dependent variations in the lamps.

2. Laboratory Work

All of the laboratory work was done at NIST. For the far UV work (Sansonetti et al. 2004) we used the 10.7-m normal-incidence vacuum spectrograph, which records the spectrum on UV sensitive photographic plates (111.5 to 182.7 nm). This is the same instrument used by Reader et al. (1990) to measure the wavelengths and intensities of the emission lines of the Pt-Ne hollow cathode lamp. For the near UV work (Kerber et al. 2006, in preparation) we used the Fourier Transform Spectrometer (FTS) located at NIST's Synchrotron UV Radiation Facility (SURF). We recorded the spectrum of the hollow cathode lamp from about 155 nm (instrumental cut-off) to about 400 nm using two different photomultiplier detectors and a filter. Although the recorded spectrum extends to 400 nm, sensitivity decreases rapidly beyond 350 nm.

Since we did not have any documentation on the wiring of the lamps, we had to establish the correct polarity by trial and error. After a few attempts all four lamps ignited and demonstrated their reliability 20 years after their first use and following a six-year period of hibernation in museums.

Exposure times on the 10.7-m spectrograph were 5.5 and 7 h for the GHRs and FOS lamps, respectively. On the FTS we coadded a few hundred spectra to obtain integration times of 4 to 6 h. The lamp current was strictly limited to 10 mA in order to match the operating conditions on the spacecraft and to minimize the risk of altering the properties of this unique hardware. In order to preserve the lifetime of the lamps, we did not attempt to obtain deep exposures. The resulting spectra contain about 700 lines for the GHRs Pt-Ne lamps, while the FOS Pt/Cr-Ne lamps yielded about 1500 lines.

Figure 1 shows an FTS spectrum and the corresponding section from the GHRs archive. A detailed analysis showed only limited variation in spectra taken on orbit and after return.

3. Analysis of the Spectra from Different Epochs

For the analysis we concentrate on the GHRs spectra because the resolutions of GHRs echelle modes and the FTS are similar, facilitating a direct comparison. We have combined spectra from the Instrument Definition Teams' pre-launch archive, the orbital archive, and the measurements at NIST, covering a time base of almost 20 years from 1984 to 2003.

First we looked for any changes in the intensity ratios of individual lines. To this end we carefully selected spectral regions which contain lines from both Ne and Pt, preferably also from different ionization stages. We chose regions at 185, 263 and 315 nm. By combining two or three echelle settings we used 15 - 25 lines in regions 5 - 10 nm wide. Figure 2

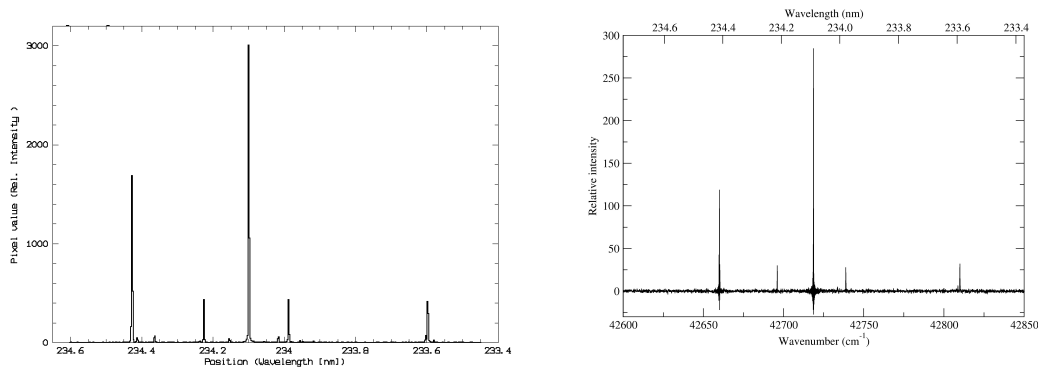


Figure 1: Sample spectrum of GHRs lamp #2. The wavelength range is approximately 233.4 – 234.6 nm. The spectrum in the left panel was taken with GHRs during orbital operations in 1994 (mode ECH B). The data were retrieved from the GHRs archive. The FTS spectrum (right panel) was obtained in the NIST laboratory in 2003.

illustrates a decrease of the observed intensity of the lines of about 25 % during the orbital phase. The lines belonging to a given element and ionization stage have been normalized to the intensity observed pre-launch and combined into an average for a given epoch. We used standard wavelength calibrations and so called SPYBAL's. A SPYBAL (Spectrum Y BALance) is a short calibration lamp exposure taken at standard wavelength settings to center the spectrum on the diode array in the cross-dispersion direction. A SPYBAL is normally taken whenever the optical element (e.g. grating) is changed. We selected wavelengths that had been observed as part of the pre-launch calibration program. The majority of the post-launch spectral calibration lamp observations are SPYBAL's. No significant differences between the individual species were found (Fig. 2). This indicates that the conditions in the discharge did not change noticeably over the years.

Comparisons between the three wavelength ranges selected show different rates of decrease at different wavelengths (Fig. 3). Based on the finding that no differences between elements and ionization stages exist, we have normalized all lines to the intensity observed pre-launch and combined into an average for a given epoch. The largest loss (approximately 45%) was found at the shortest wavelength of 185 nm. At 265 nm the decrease is about 25% while at 315 nm the behavior is not well described by a constant slope. While a decrease of the lamps' intensity over time would not be surprising, it is not evident that this should be wavelength dependent. Furthermore our accelerated aging tests (Kerber et al. 2004; 2006) on newly acquired but very similar lamps from the same manufacturer showed only very limited change in the lamps after more than 1000 h of operation. In contrast the GHRs lamps SC1 and SC2 only accumulated about 10 and 50 h respectively over a six-year period in orbit. To further elucidate the situation we made comparisons with other calibration exposures from the GHRs.

3.1. Flat Field Lamp

The GHRs used Xe lamps with major emission at 147 nm for a flat field illumination of the detectors. Light from the Xe lamps illuminated the detectors directly without any dispersing element in between. The flat field data show a monotonic decrease in intensity with almost constant slope (Fig. 4). Over the 6.5 years on orbit it amounted to a 15% loss at an effective wavelength of around 147 nm. While significant, this is far less than the 45% reported at 185 nm from the spectral lamps.

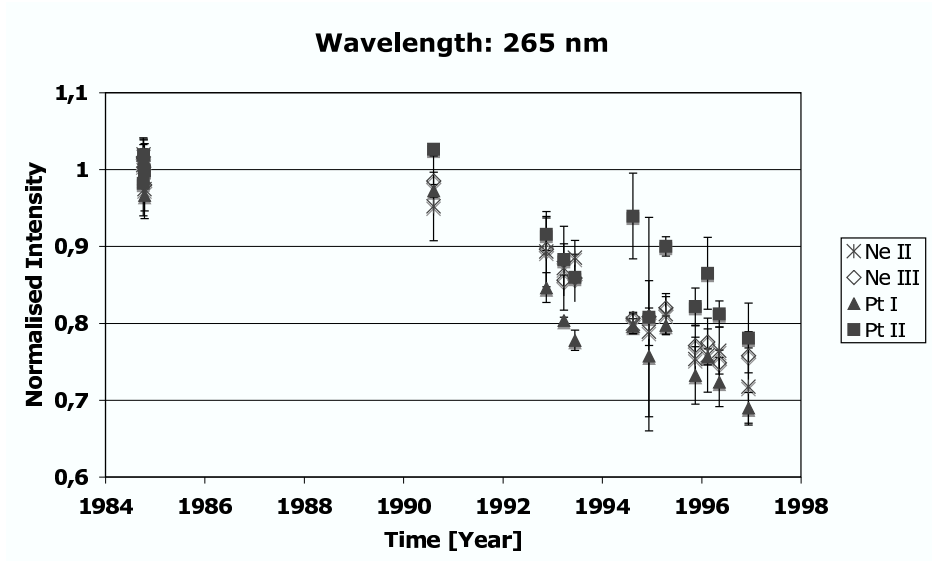


Figure 2: Change of the observed intensities of lines around 265 nm. Lines of a specific element and ionization stage have been normalized to the intensity observed pre-launch and combined into an average for a given epoch. A general decrease by about 25% is evident but no significant differences between individual species are apparent, indicating stable conditions in the discharge over the period investigated.

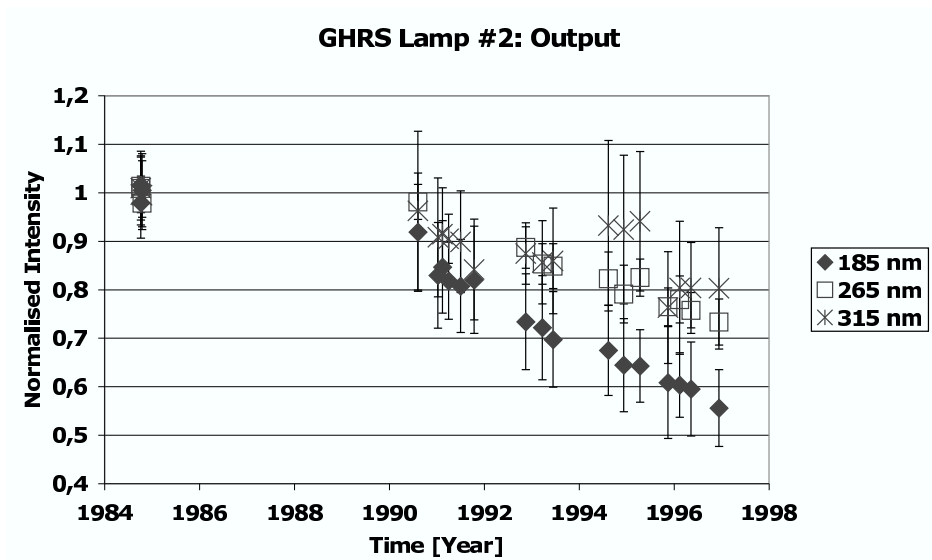


Figure 3: Change of the observed intensities of lines in three selected small (5-10 nm) wavelength bands distributed over the GHRs spectral range. Based on the finding that no differences between elements and ionization stages exist (Fig. 2) we have normalized all lines to the intensity observed pre-launch and combined into an average for a given epoch. The shortest wavelength shows a decrease of 45% in intensity while longer wavelengths show smaller losses.

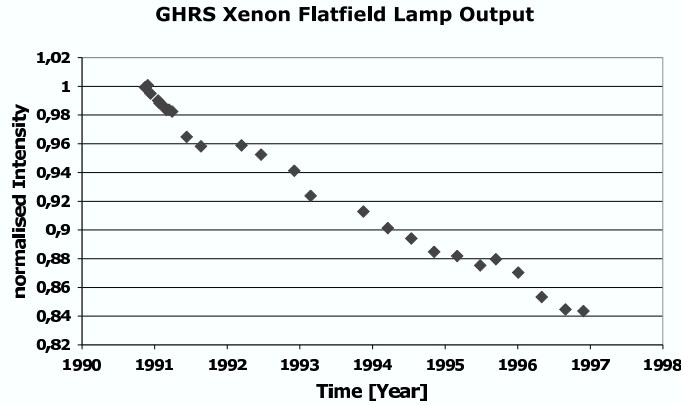


Figure 4: Change of the observed intensities of the GHRX Xe flat field lamp #2. Its main emission is around 147 nm. The intensity drops linearly over time, resulting in a 15% loss after 6.5 years.

3.2. External Calibration Source: Standard Star μ Columbae

For flux calibration, photometric standard stars were regularly observed. We have compiled a number of observations of μ Col over the complete orbital phase of GHRX. The flux of the star as observed by GHRX is constant except for a step observed in late 1993 when astronauts installed COSTAR during the first servicing mission to HST. COSTAR was an optical kit designed to compensate for the optical flaw of HST's primary mirror. Its components deliver the inverse of the spherical aberration, restoring the full imaging capabilities of the HST. COSTAR provided a highly improved point spread function (PSF) concentrating about 80% of the light in the central peak. This allowed more light to enter the slit of the HST's spectrographs while introducing two additional reflective surfaces in the optical path. In the case of the GHRX the net effect of COSTAR is illustrated by observations of the standard star μ Col (Fig. 5). The relative importance of the improved PSF (reduced slit losses) and added reflective losses explains the behavior after the end of 1993. At short wavelengths, the two additional reflections cause a net loss in sensitivity while at longer wavelengths the improved PSF leads to progressively better sensitivity. In Figure 5 three wavelengths closely corresponding to the wavelengths bands observed with the spectral lamps have been plotted. To facilitate comparison the fluxes in two of the bands have been multiplied by an appropriate factor. Except for the step, just explained, the flux of the standard star is highly constant.

4. GHRX Optical Layout and Interpretation of the Behavior of the Lamps

The observations of the standard star demonstrate that the performance of the elements of the light path for an external source were highly constant throughout the lifetime of the GHRX. The 15% decrease in intensity of the flat field lamps very likely originates in the lamps themselves since they illuminate the detectors directly without any optical elements in between (Fig. 6). The flat field lamps are Xe discharge lamps with a design not unlike the Pt-Ne spectral lamps. Light from the calibration lamps is reflected by two folding mirrors (Fig. 6, only one of the two mirrors shown) before it enters the spectrograph slit and from there on it shares the full optical path with an external target such as μ Col. Given the fact that the conditions in the discharge also do not seem to change over time (Fig. 2) we have to conclude that the observed wavelength dependent changes arise from changes in the

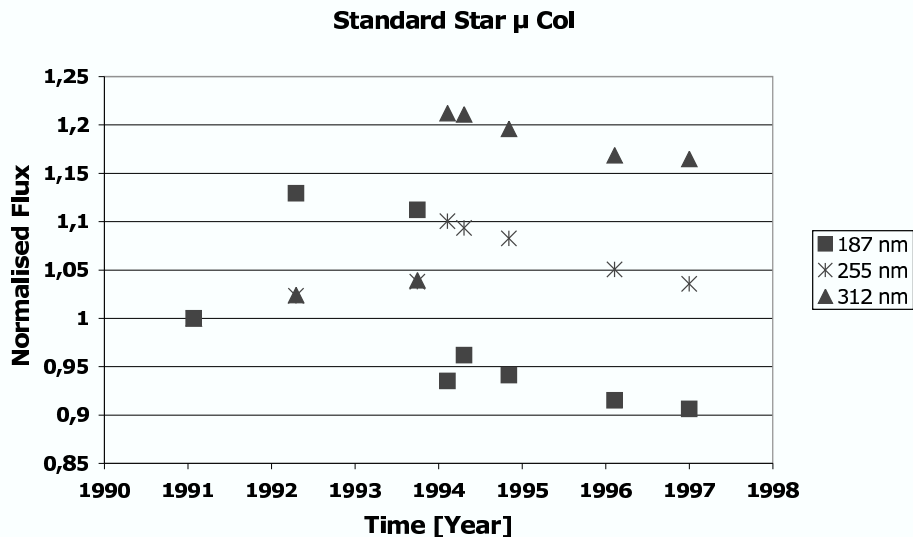


Figure 5: Observations of the standard star μ Col during GHRs orbital operations. Three wavelengths closely corresponding to the wavelengths bands observed with the spectral lamps (Fig. 3) have been plotted. To facilitate comparison the fluxes in two of the bands have been multiplied by an appropriate factor. Except for a step introduced by the addition of COSTAR (details in the text) the fluxes are constant to within 5%.

optical properties of either the lamp's window or the two MgF_2 surfaces directing the light to the spectrograph.

5. Summary

- We have assembled a unique data set spanning a period of 20 years consisting of spectra taken before launch, during operations in orbit, and after return of the four GHRs and FOS lamps.
- The lamps still work perfectly after 20 years and the conditions in the discharge seem to be constant in time, confirming that hollow cathode lamps are very reliable and stable sources for wavelength calibration.
- This stability is confirmed by accelerated aging tests of lamps similar to those used on GHRs, FOS and STIS extending to operating times well in excess of 1000 h.
- The data show some change in the intensities as observed over time. Careful analysis suggests that these can be attributed to optical components in the light path, specifically the two reflective prisms or the lamp windows.
- Hollow cathode lamps have previously been suggested as secondary radiometric standards (Klose, Hartig & Rosenberg, 1990) for monitoring changes in the optical path. Further investigations to this end are recommended.

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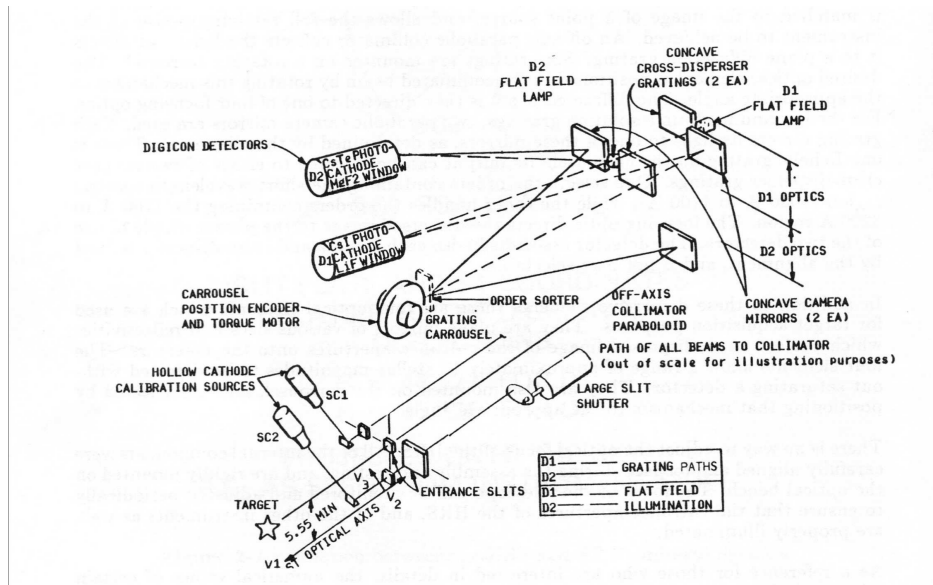


Figure 6: Schematic drawing of the GHRS optical system. (Not all optical elements shown.)

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