Rectification of FOS wavelength scales

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A status report on the ST-ECF Post-Operational Archive (POA) project to re-calibrate all Faint Object Spectrograph (FOS) data is presented. As a first step we have investigated the internal zero-points of the FOS on-orbit wavelength calibration between 1990 (launch) and 1997 (decommissioning). The analysis is based on more than 3,000 calibration and science exposures. For the FOS/BLUE channel, systematic shifts of the zero-points are present which amount to a maximum offset of 7 pixels (350 km sec^{-1}) over the instrument orbital life. In contrast, the zero-points for FOS/RED modes present an apparently random distribution with the same peak-to-peak range of 7 pixels. Both problems cannot be accounted for by mechanical or thermal instabilities, but have been traced to the influence of the geomagnetic environment of the spacecraft. A new version of the pipeline will be made available and used for a complete re-calibration of the FOS science archive.

Introduction

Calibrating astronomical data from instruments on spacecraft is complicated by the fact that only a small fraction of the time can be used for dedicated calibration exposures. Therefore a 'final' calibration is achieved only after years of operation, or even after the end of an experiment's operational life (eg, IUE, IRAS, ISO).

The POA project aims to improve calibrations for the decommissioned HST instruments. The FOS was chosen as the first instrument of the POA effort in part due to the expertise acquired at the ST-ECF since 1984. In order to achieve the comprehensive understanding required for a successful re-calibration of the 17,000 FOS science observations, all of the data are now being subjected to dedicated analyses. So far, the issue found to be most pressing is an unacceptably large uncertainty in the FOS wavelength calibration.

The FOS was designed primarily as a faint object spectrophotometer, with less emphasis placed on highly reproducable velocity measurements. Observers planning to use FOS data for radial velocity studies were advised to obtain their own dedicated wavelength calibration observations in sequence with the science exposures and without aperture or grating wheel movements. In reality, only very few FOS programmes obtained exposures planned in this manner.

According to the instrument specification, the main intrinsic errors in the wavelength scale zero-points reflected the settling of the rotating filter-grating wheel assembly (FGWA), uncertainties in the centering of point sources in the aperture and the offsets between internal (calibration lamp) and external sources. These effects should amount to a total 1σ error budget not exceeding 2 pixels (0.5 diodes or approximately 0.25 resolution elements, cf. HST Data Handbook). The dispersion relations, monitored by calibration lamp exposures, did not directly show any suspicious behavior. Therefore, the original set of dispersion solutions, which were a product of the science verification (SV) activity, was used throughout the entire operational life of FOS as the default in the pipeline calibration.

Nevertheless, during the operating life, indications were accumulating that FOS wavelength scale zero-points might occasionally be considerably more in error than the fractional diode value mentioned above (eg, van der Marel, 1997).

Preparation of data

Usually FOS WAVECAL exposures are analysed by fitting low order polynomial dispersion solutions to the line center catalogues. Such a procedure may not reliably detect zero-point shifts from polynomial coefficients. Therefore, we chose to cross-correlate the raw exposures, taking as templates those exposures used during SV dispersion analysis (cf, CAL/FOS 67) which also defined the dispersion relations throughout the entire life of FOS in the *calfos* pipeline. The WAVECAL analysed cover the whole period between SV (August 1990) and the last on-orbit wavelength calibration observation obtained (December 1996). Cross-correlation of the data sets for all high resolution modes yields a very clean peak which can be positioned to better than 0.1 pixel (3σ) using Gaussian profile fitting.

We also prepared a sample of suitable scientific exposures for a complementary analysis. For this purpose we chose narrow emission line spectra (ie, H II regions and PNe) and extracted about 100 high S/N spectra from the archive. These data come from 15 different objects covering three different gratings (G400H, G570H, G780H), a number of apertures and a wide time span. Again, we used cross-correlation to derive the zero-point shift of the wavelength scale. We specifically built templates from the superposition of Gaussian profiles located at the laboratory wavelengths for all relevant lines in the observed spectra. With this approach, an accuracy of better than 0.1 pixel was achieved. The zero-points obtained were corrected for Heliocentric motion and the radial velocities of the targets taken from the literature. For extragalactic sources we adopted the values from the 'Third Reference Catalogue of Bright Galaxies' (de Vaucouleurs et al., 1991). Usually, the error margins for the sum of these corrections are between 5 and 30 km sec^{-1}. This is the largest source of uncertainty in the analysis of the scientific data set. For this reason we did not correct for the orbital motion of the HST.

Quick analysis

For the analysis, we broke down the samples according to detector, grating and aperture, and plotted the zero-point shifts of the WAVECALS versus the Modified Julian Date (MJD) of exposure start. This comprehensive view revealed substantial shifts for all FOS dispersers.

All of the FOS/BLUE dispersers show a very similar and conspicuous pattern with time (Figure 1). At any given epoch, the peak-to-peak scatter of the zero-point offset about the mean trend is approximately ±1 pixel (ie, 10 times the measurement error). The general trend amounts to an average drift of 0.75 pix yr^{-1} with respect to the zero-point of the pipeline wavelength scale for each disperser. An observation in Cycle 6 therefore might be off by more than 5 pixels from nominal (~300 km sec^{-1} for the high resolution dispersers, ~1400 km sec^{-1} for low resolution G160L and ~4000 km sec^{-1} for the little-used G650L).

Due to the apparent similarity in the pattern for all blue

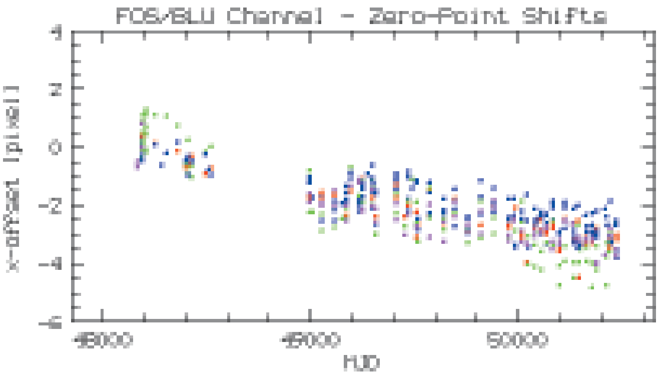

Figure 1. Zero-point offsets (in pixels) of the wavelength scale for high-resolution modes on the FOS/BLUE side as a function of time (Modified Julian Date). Different colours denote the various high-dispersion modes. Note the nearly linear trend and the segregation into 3 epochs, namely the time before on-board GIMP correction, the short period before SM 1, and the long timespan with on-board GIMP after CO-STAR installation during SM 1.

dispersers we combined all FOS/BLUE high-resolution and G650L grating data into a common dataset, depicted in Figure 1. This was done iteratively. A full combination, very similar to Figure 1, was used to define three windows in time within which the data appear to follow different linear trends.

Interestingly, the boundaries of these windows coincide with the start of SV, the activation of on-board GIMP correction, the installation of COSTAR and the decommissioning of FOS. The gap between MJD 48,500 and 49,000 corresponds to the epoch where the geomagnetically-induced image motion problem (GIMP, see also below) was known, but before on-board correction became available. No FOS data were taken during this period. An empirical solution to the problem is rather straightforward: linear regressions were fitted to the data in these three windows, and were subsequently used to renormalise the shifts for each grating/aperture combination. The renormalisation usually was less then 0.2 pixel, for all but two gratings. This fix was made available in late 1998:
`http://www.stecf.org/poa/FOS/fosbl_wcorr.htm`
For a detailed description see CAL/FOS 149.

At first glance the data for the red side (Figure 2) appear to present a scatter-diagram with no obvious trends in time and with a full peak-to-peak range of about 6 pixels. A simple quick fix as provided for the blue side did not seem possible.

Detailed analysis

In preparing a refined version of the FOS POA, a proper analysis and corrective measures based on physical models is

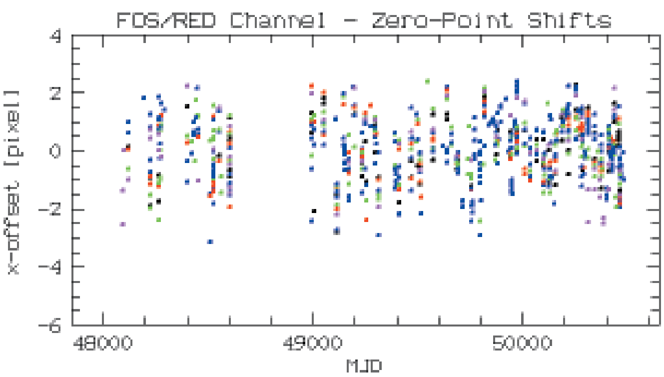

Figure 2. Zero-point offsets (in pixels) of the wavelength scale for high-resolution modes on the FOS/RED side as a function of time (Modified Julian Date). Different colours denote the various high-dispersion modes. Note the large scatter and the absence of an obvious correlation with epoch.

mandatory. In contrast to the original researcher who could tailor the observations to the scientific goals, such as bracketing the target exposures by WAVECALS for radial velocity studies, the archive reasearcher has no such influence on the data taking strategy. Consider for example a project to study velocities of emission lines in the sample of all AGNs ever observed with FOS. Even if the intrinsic width of the emission lines is around 1000 km sec^{-1}, a systematic, non-random error of the zero points of order 300 km sec^{-1}—as exists in the current version of the FOS archive—will seriously degrade the results. Therefore, the wavelength scale zero-point problem has been rated with a severity value of 6 on the POA scale:
`http://www.stecf.org/poa/images/poascale200.jpg`

The behavior of the FOS/RED and /BLUE channel wavelength zero-points are dramatically different, whereas the optical and mechanical layouts of the two channels are identical. Hence, the error is most likely to be associated with the detectors themselves. In particular, those parts of the system shared by both channels, eg, the apertures and the gratings, can be excluded as the cause of the scatter. The one known major difference between the two detectors is a factor of ten less efficient magnetic shield for the red Digicon. The lower shielding results in an imprint of the geomagnetic environment on the electron optics inside the Digicon. The related geomagnetically induced image motion problem (so-called GIMP) had been identified some time after launch, and a corrective procedure has been applied on-board to all observations from April 1993 (cf, CAL/FOS 098).

The secular trend in the blue channel may therefore be related to a slow magnetization of a near ideal mu-metal screen, while the red side Digicon data might suffer from a problem related to the on-board GIMP compensation. Unfortunately we found the on-board flight software to have been incorrectly implemented, leading to an artificial increase of the image motion for a substantial fraction of the observations. In the course of this investigation we therefore developed our own (POA) GIMP correction algorithm, which has been demonstrated to successfully correct data sets obtained prior to the on-board patch to better than a small fraction of a pixel. The residuals to be expected from a particular sequence of observations during half of an HST orbit with the flight software (FSW) algorithm are compared with the POA algorithm in Figure 3.

Additional insight is gained by analysing the science observations, since these were 'pointed' and obtained in only the 'science' parts of orbits, whilst the WAVECAL were mostly obtained during earth occultation. In Figure 4 the

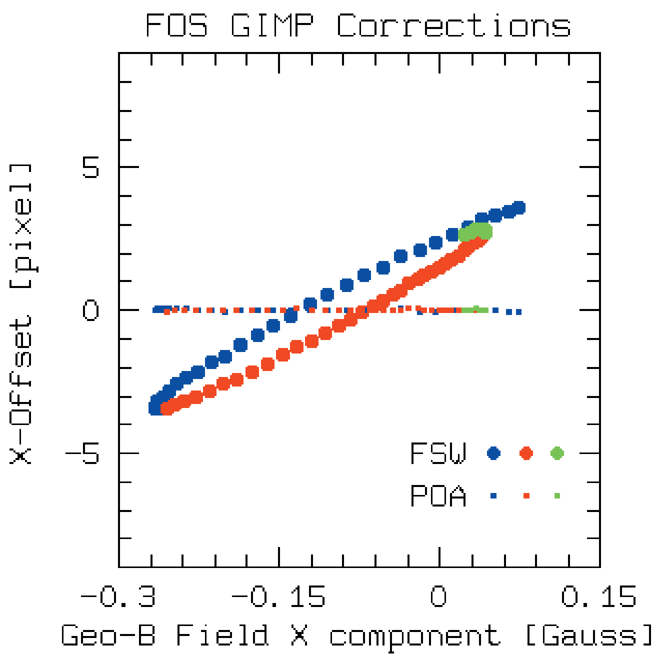

Figure 3. Comparison of the residual zero-point shift after a GIMP correction has been applied to a continuous sequence of observations during approximately half an orbit. The colours depict the location of the spacecraft in 3 of the 4 quadrants in geocentric longitude. In the case of the flight software (FSW) correction, major deviations and a dependency on the x-component of the magnetic field remain, indicating that the GIMP corrections was not successfully implemented. For our new algorithm (POA) the residuals correspond to only a small fraction of a pixel.

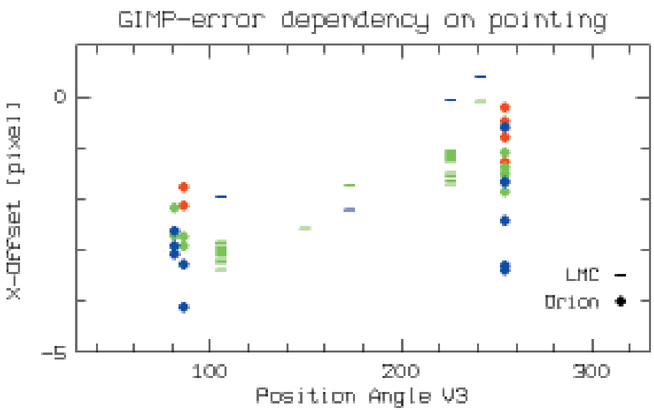

Figure 4. Dependence of the GIMP error on the pointing of the HST for a sample of scientific observations of targets in the LMC and the Orion nebula taken at different dates. Observations in the LMC show a considerably smaller internal scatter but a pronounced linear dependency on the position angle of the spacecraft. Again colours are used to differentiate between different gratings.

offsets of the wavelength scale are shown as a function of the roll angle of the HST for a subsample of science observations performed with GIMP on-board correction. If the on-board correction had worked as intended, there should be only a minimal range of residual offsets (ie, fraction of a pixel) and there should in no case be a dependency on roll angle of the spacecraft.

Corrective measures

At this point it is obvious that, in principle, the way to correct all observations is to first undo the on-board correction and then apply the new POA-GIMP correction. The geomagnetic environment of the FOS detector is directly related to HST's position in orbit and its orientation. Therefore a successful re-calibration not only rests upon correct algorithms, but equally well on the knowledge of the pertinent parameters used for the on-board GIMP procedure in the first place.

An improved *calfos* pipeline that rectifies the wavelength scales as discussed above has already been set up. It is planned to make it available to the community in 2000. The main reason for not releasing it right now is related to evidence that crucial header information (eg, time, ephemeris and pointing) occasionally is inconsistent or incorrect. Once this issue has been resolved the new *poa-calfos* pipeline will restore the accuracy of the wavelength calibrations of all scientific observations to within one pixel. Scientifically this will recover the original specification goal of the FOS and reduce the current uncertainty 300 km sec^{-1} down to the design value of 60 km sec^{-1} for the FOS high resolution modes.

References

All referenced Instrument Science reports CAL/FOS are available online at the POA site:
`http://www.stecf.org/poa/FOS/fos_bib.html`

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