Testing the Defringing Tool Suite on the Time Dependent Sensitivity Data

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ABSTRACT

STIS CCD spectroscopic observations taken with gratings G750L or G750M are strongly impacted by fringing at wavelengths >7500 Å. The STIS team recently ported the original `IRAF/PyRAF` *defringing tools to the* `stistools` *Python package, which include four essential tools to correct for this effect:* `normspflat`, `prepspec`, `mkfringeflat`, *and* `defringe`. *In this ISR we describe the testing done on the new* `stistools.defringe` *package. We re-analyze the G750M and G750L spectroscopic observations taken as part of the calibration programs for the STIS CCD Spectroscopic Sensitivity Monitor, and perform a full time dependent sensitivity (TDS) analysis on fringed and defringed observations. A comparison of the TDS results from the fringed and defringed observations shows that the calculated sensitivity slopes are identical for wavelengths <7500 Å. At longer wavelengths we find that the defringed data provide slightly different slopes than the fringed observations, however, these values are always within the uncertainties. Overall, we show that the defringing tools successfully improve the quality of the science spectrum, removing these interference features from both G750M and G750L exposures.*

Contents

1. Introduction

STIS CCD spectrocopic observations taken with gratings G750L or G750M are strongly impacted by "fringing" at wavelengths >7500 Å. According to Goudfrooij et al. (1998) these features are caused by interference of several CCD reflections where the wavelength of the incident light is a small integer multiple of the distance between the two CCD surfaces. The STIS team recently ported the original `IRAF/PyRAF` defringing tools to the `stistools Python` package, which include four essential tools to correct for this effect: `normspflat`, `prepspec`, `mkfringeflat`, and `defringe`.

To test the new `stistools.defringe` package, we re-analyze the G750L spectroscopic observations taken as part of the calibration programs for the STIS CCD Spectroscopic Sensitivity Monitor. We highlight that an effort was made to also test the G750M mode included in the CCD sensitivity monitor, however, the wavelength coverage of the G750M grating using a central wavelength of 7283 (6997-7569 Å) is not strongly affected by fringing. We find that defringing the G750M/7283 observations has only a minor, or no effect, on the final product (see bottom panel in Figure 2). Due to the low impact fringing has on the G750M/7283 setting, we limit our STIS time dependent sensitivity (TDS) testing to the G750L observations. In Section 7, however, we detail the steps performed on the G750M observations, and identify a STIS CCD observation using the G750M grating with a central wavelength of 8561 Å, relevant to our defringing testing.

The TDS G750L analysis involved four different steps: 1) Downloading of the data for the different cycles, 2) Fixing jitter induced combination errors in problematic datasets, 3) Applying fringing correction with `stistools.defringe`, 4) Re-analyzing the observations to measure the STIS TDS. We describe in the following sections each of these steps in more detail.

2. Downloading STIS observations

Using the STIS Calibration Program Tables[1], we identified the calibration program IDs of the CCD Spectroscopic Sensitivity Monitor for Cycles 7-12 (pre-SM4) and 17-26 (post-SM4). In Table 1 we list the different programs, their corresponding PIs, and any problematic exposures (see Section 3). We retrieved the raw and calibrated STIS observation from the Mikulski Archive for Space Telescopes (MAST). We downloaded exposures using both gratings, G750M and G750L, and 52X2 and 52X2E1 apertures.

3. Correcting for jitter induced CCD combination errors

According to Carlberg (2019), STIS CCD exposures are split into different sub-exposures to facilitate the removal of cosmic rays. The cosmic ray (CR) removal algorithm assumes that the individual sub-exposures are well-registered. The algorithm fails when the target moves drastically within the spectroscopic slit during the observation due to telescope jitter. For these exposures the software then rejects a large fraction of useful data, causing the target fluxes to be underestimated. Carlberg (2019) recommends an efficient way of identifying an over-rejection of CRs using the `calstis` CR-rejection algorithm involving the comparison of the fraction of CR-rejected pixels in the extraction region with that of the full detector. This can be done using the `stistools.crrej_exam` function.

Several STIS CCD exposures in the HST calibration programs listed in Table 1 have been identified to suffer from these jitter induced combination errors. We list in the fourth column of Table 1 the exposures impacted by these jitter induced problems. As recommended by Carlberg (2019) we recovered the discarded counts by increasing the threshold for rejecting pixels set by the parameters in the CR-rejection algorithm. We re-ran the `ocrreject` function in the `stistools` package changing the initial guess (INITGUES) from the standard minimum to median, and the statistical rejection criteria (CRSIGMAS) from 4 to 10.

Re-running the `ocrreject` software on the problematic exposures listed in Table 1 improved the calibration of the observations, with the exception of dataset oceil4060. Given that for this exposure we were unable to obtain a reasonable percentage of pixels rejected as CRs, we exclude this dataset from our TDS analysis.

4. Defringing STIS CCD G750L observations

After installing the `stistools` package as instructed in their official page[2], we ran a few quick tests to make sure the tools had been properly installed.

To run the different steps needed to fully correct for fringing in the STIS

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[1]https://www.stsci.edu/hst/instrumentation/stis/calibration
[2]https://stistools.readthedocs.io/en/latest/gettingstarted.html

Table 1.: Proposal information of the STIS CCD Spectroscopic Sensitivity Monitor programs analyzed as part of our test

Cycle	PID	PI	Problematic exposures
7	7672	Walborn	o45a03030, o45a14030
8	8418	Walborn	o5ig05030, o5ig03030
9	8856	Walborn	
10	8914	Walborn	o6i904050, o6i904060
11	9627	Walborn	
12	10030	Friedman	o8u207060, o8u204060
			o8u206060
17	11855	Proffitt	obau02060, obau03060
			obau05060, obau01060
18	12411	Osten	obmzl1050
19	12772	Bostroem	
20	13141	Holland	
21	13544	Sana	oceil4060†
22	13991	Sana	
23	14423	Monroe	
24	14829	Monroe	odbvl1050
25	14970	Carlberg	
26	15558	Carlberg	

†Dataset excluded from TDS analysis.

observations, we created the Python script `defringe_TDS.py` (see Appendix). The script iterates on the different data directories containing the exposures from the different HST calibration programs. For each science exposure, the code identifies the associated fringe flat recorded in the header keyword FRNGFLAT. One of the first steps is to normalize the fringe flat using the `stistools.defringe.normspflat()` function. Given that the G750L fringe flats include some fringes at wavelengths <6000 Å caused by an order-sorter filter, the `defringe_TDS.py` script flattens the blue end of the flat-field image as these fringes are already included in the sensitivity function.

After normalizing and flattening specific regions of the fringing flat the script calls the `mkfringeflat` function to create the final fringing flat matching the fringes in the science exposure. `mkfringeflat` calculates the appropriate shifts and scaling factors needed to match the fringes in the flat and the science exposures.

We find that using the default values controlling the searching ranges and steps serve our exposures well. One critical difference when running `stistool.defringe.mkfringeflat()` on the G750L 52X2 compared to the G750L 52X2E1, is the need to manually specifying the location of the extracted spectrum using the extrloc parameter. Since the 52X2E1 aperture places the science spectrum around row 900, near the CCD readout amplifier, after visually inspecting the science exposures we set the extrloc=894.

To correct the science exposures the script divides the scientific image by the shifted-and-scaled fringe flat using the `stistools.defringe.defringe()` tool. As a final step, we then extract the target spectrum using the `stistools.x1d.x1d()` function. In our analysis the final defringed extracted spectrum has an extension of *_dsx1.fits. We show in the top panel of Figure 2 a comparison between a standard fringed STIS G750L spectrum (black) and the final corrected STIS spectrum (red).

5. Post-SM4 Hot Pixels on the G750L/52X2E1 data

We identified a few persistent hot pixels on the G750L/52X2E1 observations taken Post-SM4, not present in the Pre-SM4 data (Figure 1). These hot pixels are flagged with DQ values of 16 (Pixel having dark rate $> 5\sigma$ times the median dark level), but not excluded from the final calibrated product. The inclusion of such pixels in our TDS analysis provides a biased estimate of the sensitivity slopes, particularly for those wavelength bins containing these hot pixels. Before continuing with the TDS analysis, we modify `tds_analysis.py` code to interpolate over pixels flagged with DQ=16, similar to what it is currently done for the saturated pixels. We note that such a modification to the TDS software has a minor impact on the sensitivity slopes for those wavelengths outside of the bins containing the hot pixels.
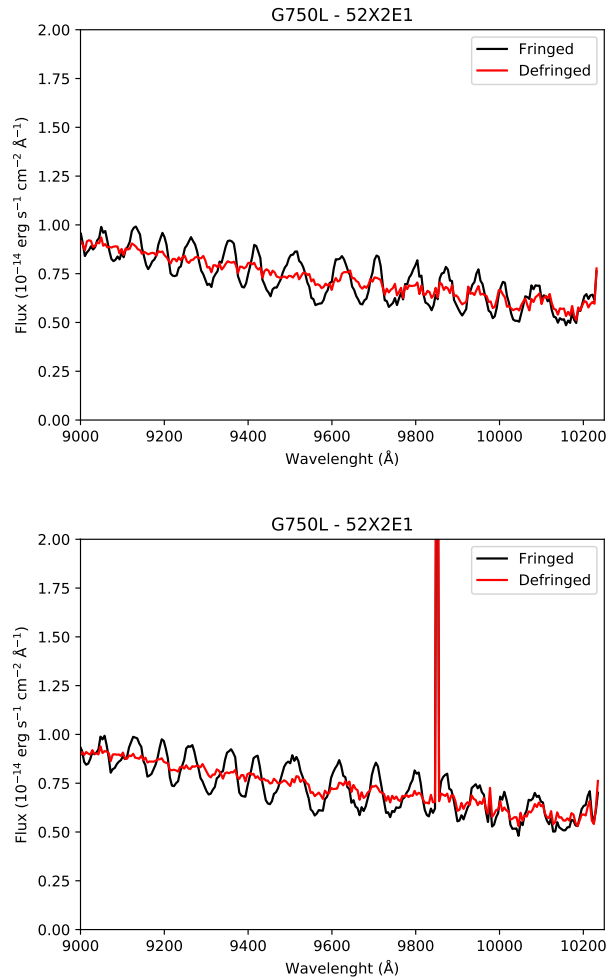
Figure 1.: *Top:* Comparison between a standard fringed STIS G750L/7751 spectrum (o6i903050) in black, and the same spectrum corrected for fringing in red for an exposure taken Pre-SM4. *Bottom:* Same as the top panel for an exposure taken Post-SM4 (obau02050). Note the clear appearance of hot pixels at wavelengths > 9800 Å in the Post-SM4 spectrum.

6. TDS analysis

The main goal of the TDS analysis is to characterize CCD sensitivity trends correlated with time after accounting for known throughput variations (e.g., charge transfer inefficiencies, and temperature effects). The TDS software calculates the relative sensitivities and plots them as a function of time fitting linear segments. This is done for different wavelength bins, calculating the slopes in the data, i.e. percent-per-year change in sensitivity. After modifying the TDS software as described in Section 5, we then ran the TDS code on two different sets: 1) fringed *_sx1.fits and 2) fringe-corrected *_dsx1.fits. Note that each set includes observations using the G750L/52X2 and G750L/52X2E1 settings.

We first ran the fringed observations through the TDS software and found that the code fits a single linear function to the whole sample (for both G750L/52X2 and G750L/52X2E1), covering Cycles 7-12 (1997-2003, Pre-SM4) and 17 to 26 (2009-2019, Post-SM4). This single-slope approach is similar to what has been adopted in previous G750L TDS studies (Carlberg & Monroe 2017). Given that correcting for fringing in the STIS CCD data will primarily impact the reddest wavelengths, we show in the left panels of Figure 3 the observed trends in the relative sensitivity of the STIS CCD G750L grating using the 52X2 (top) and 52X2E1 (bottom) apertures as a function of time for the 8700-Å bin. One of the main differences between the observed TDS trends in these two CCD modes is the larger scatter in the G750L/52X2E1 setting, compared to the nominal G750L/52X2 mode. We calculate a slope of -0.270 ± 0.004 % yr^{-1} for the 8700-Å bin for the nominal 52X2 aperture, and a slope of -0.216 ± 0.008 % yr^{-1} for the same bin for the 52X2E1 aperture.

We proceed to run the same algorithm on the defringed STIS observations. We show in the right panels of Figure 3 the observed trends and fits of the defringed observations, both for the 52X2 (top) and 52X2E1 (bottom) apertures. We calculate a slope of -0.285 ± 0.004 % yr^{-1} for the G750L/52X2 setting and a slope of -0.208 ± 0.008 % yr^{-1} for the G750L/52X2E1 setting. We note that the slope calculated from the defringed data for the 52X2 setting is slightly lower than that from the fringed observations for the 8700-Å bin. This is in contrast to the values calculated for the 52X2E1 setting, where the slopes for the fringed and defringed observations are comparable and within their uncertainness. We also note the large scatter in the 52X2E1 panels in Figure 3. This trend appears to increase with time, and it is reflected in the slope uncertainties as well (Figure 4). Such an effect has been reported in previous studies (e.g., Carlberg & Monroe 2017), however, this new defringing analysis shows that the uncorrected fringe patterns were not the main cause of the observed scatter.

In an effort to test the new STIS CCD defringing tool, and to identify any differences in the results of the TDS analysis of fringe-corrected vs fringed observation, we now compare the obtained slopes from the two sets using the two G750L settings (52X2 and 52X2E1). In Figure 4 we show in the top panel the TDS slopes for the different wavelength bins for the G750L 52X2 setting, and in the bottom panel for the G750L 52X2E1 setting. In general, we see that the sensitivity of the STIS CCD detector for the G750L grating at wavelengths of ~5500 Å at the E1 aperture location (CCD row ~ 900) declines at a comparable rate as that of the center of the detector (standard extraction region on row ~ 500). In contrast, the sensitivity for this same grating at longer wavelengths, ~ 9500 Å, decreases more rapidly at the center of the detector than at the top of the detector (row ~ 900). As expected, there are no differences in the calculated TDS slopes for wavelengths < 7000 Å between the fringed and defringed data, as the IR fringes in the STIS CCD observations are strongest at longer wavelengths. For the G750L 52X2 setting, defringing the STIS observations before performing the TDS analysis returns slightly shallower slopes than
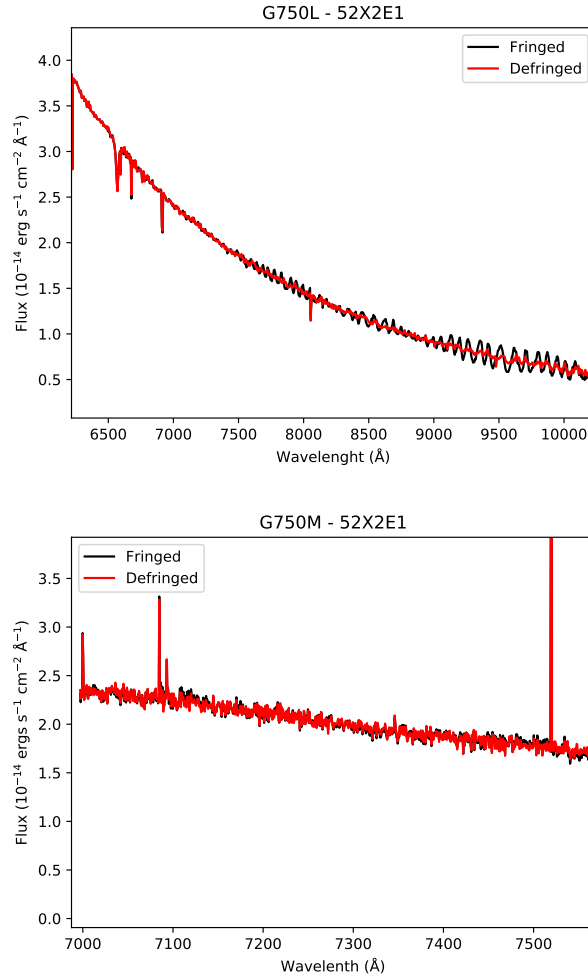
Figure 2.: *Top:* Comparison between a standard fringed STIS G750L/7751 spectrum (o6i904050) in black, and the same spectrum corrected for fringing in red. *Bottom:* Same as the top panel for G750M/7283 spectrum (obau210h0).

those from fringed data at wavelengths between 8000 Å $< \lambda <$ 9500 Å. This in contrast to the slopes for the G750L 52X2E1 configuration. For this mode we instead find that defringed observations provide shallower slopes than those calculated from fringed observations at wavelengths between 8000 Å $< \lambda <$ 9500 Å. We note, however, that the differences between fringed and defringed slopes for both settings are relatively small, and in the case of the G750L 52X2E1 data, the slopes from the two sets (fringed and defringed data) are within the uncertainties of each other (Figure 4).
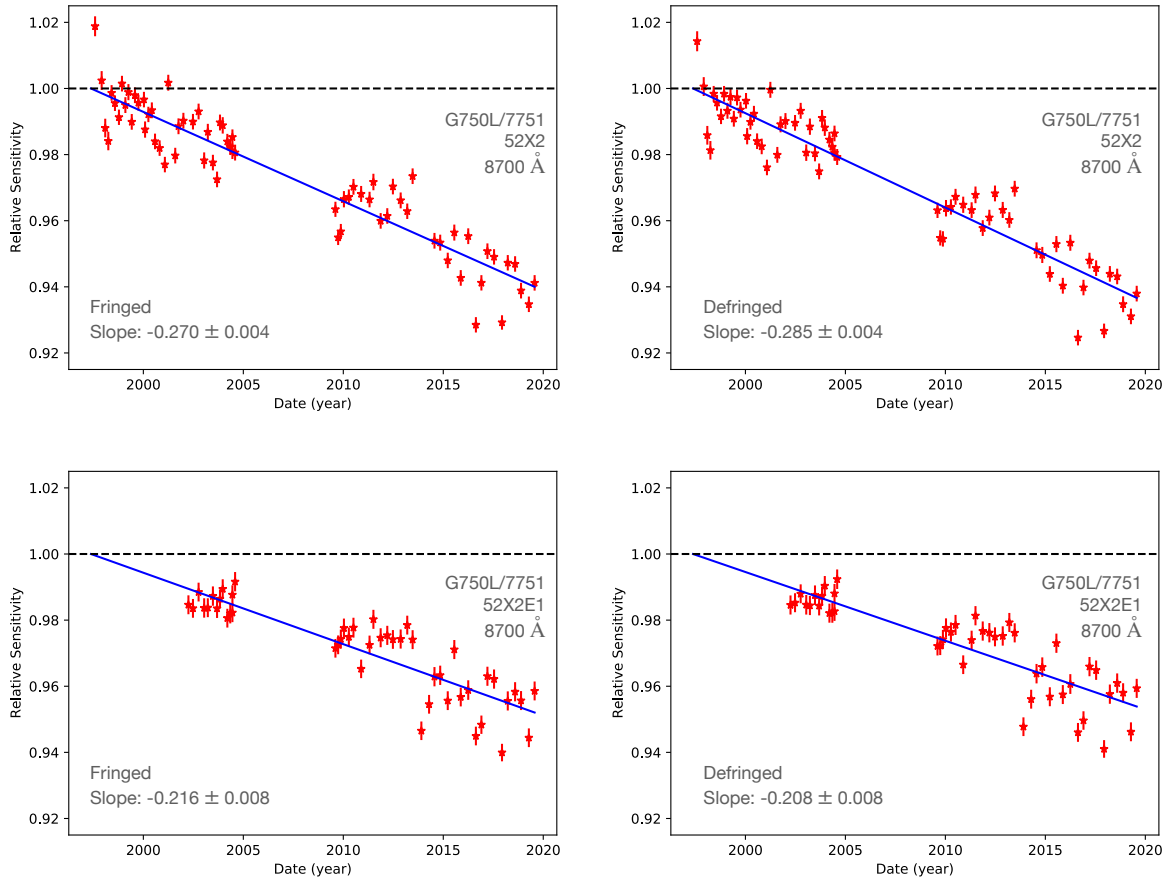
Figure 3.: *Top left:* STIS CCD Relative sensitivity as a function of time for the G750L grating using a 52X2 slit at wavelengths ~ 8700 Å for the fringed observations. *Top right:* Same as the left panel, for fringed-corrected data. *Bottom left:* STIS CCD Relative sensitivity as a function of time for the G750L grating using a 52X2E1 slit at wavelengths ~ 8700 Å for the fringed observations. *Bottom right:* Same as the left panel, for fringed-corrected data.
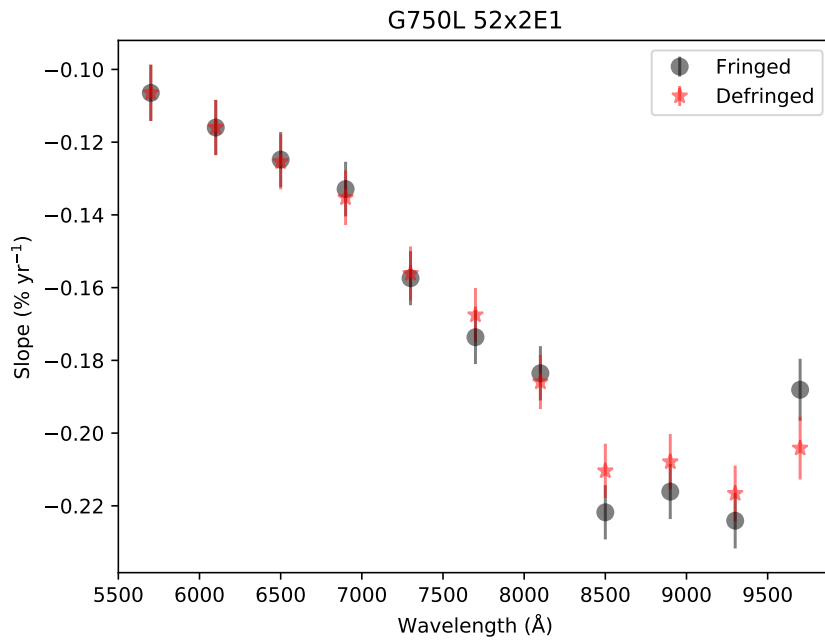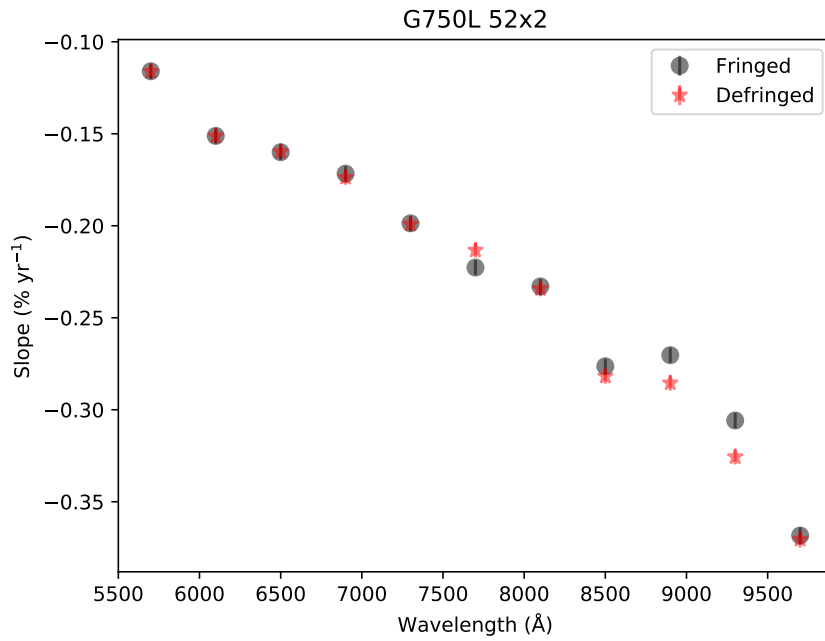
Figure 4.: *Top:* TDS for the G750L 52X2 setting calculated from fringed (black) and defringed (red) STIS data. *Bottom:* Same as left panel for the G750L 52X2E1 setting.

7. Defringing STIS CCD G750M observations

As mentioned above, we defringed the G750M observations taken as part of the STIS CCD Spectrocopic Sensitivity monitors. However, a direct comparison between fringed and defringed TDS data did not provide useful results, as the central wavelength used in the TDS observations (7283 Å) does not cover the regions strongly affected by fringing (right panel in Figure 2). For completion, we identify, download and defringe the STIS CCD dataset of the HST spectrophotometric standard BD+75D325, observed with the G750M/8561 setting and the 52X2 aperture (PID: 7810, o4lu01010). The wavelength coverage of this observation, 8275-8847 Å, is strongly impacted by fringing, particularly at wavelengths > 8500 Å. This makes the o4lu01010 dataset an ideal exposure for testing the new defringing tool on the G750M grating.

To obtain the best results, we must use the geometrically corrected G750M products when correcting for fringing. This is a critical difference between the G750L and G750M analysis. When using the `mkfringeflat` and `defringe` functions we use the *_sx2.fits files as input for the G750M data, and *_crj.fits for the G750L mode.

A final step when correcting for fringing is to extract the 1D spectrum from the fringed-corrected 2D image (*_drj.fits for G750L, and *_s2d.fits for G750M). For G750L data, we can typically extract the 1D spectrum using the `stistools.x1d.x1d()` function, however, we highlight that at this time the existing extraction routines are not able to provide 1D spectra from the geometrically rectified products, i.e. *_sx2.fits or *_s2d.fits. Instead, we perform a manual extraction using the fringe-corrected image (*_s2d.fits). To roughly extract the science spectrum we make use of the header keywords CRPIX2 (y-coordinate of reference pixel) to identify the y-location of the target spectrum, and DIFF2PT (Diffuse to point source conversion factor) to make approximate corrections for point-source specific aperture throughput and wavelength-dependent encircled energy corrections. The extraction is done by summing over 7 rows around the reference pixel (CRPIX2).

In Figure 5 we show a comparison of the fringed-extracted and the defringed-extracted spectra. The strong fringing at > 8500 Å is clearly ameliorated after running the STIS observation through the defringing tool suite.

8. Conclusions

We tested the recently ported `stistools` defringe package. We corrected TDS observations using G750L/52X2 and G750L/52X2E1 settings and find that the standard parameters on the `stistool.defringe.mkfringeflat()` function are adequate to correct G750L observations. A particularly important step when creating the fringed-aligned flat requires the user to specify the extraction location (extrloc) when correcting 52X2E1 observations.

Our comparison of the TDS analysis of the fringed and defringed data shows
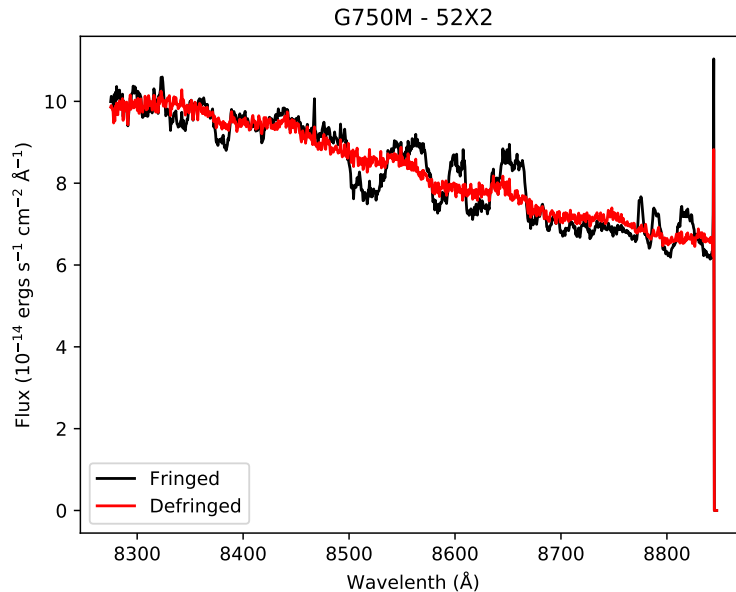
Figure 5.: Comparison between the fringed STIS G750M/8561 spectrum (o4lu01010) in black, and the same spectrum corrected for fringing in red.

that the calculated sensitivity slopes are similar for wavelengths <7000 Å. At longer wavelengths we find that the defringed data provide slightly different sensitivity slopes, however, these differences are minor, and in most cases within the uncertainties of those calculated from the fringed observations. Overall, this work validates previous TDS analyses, suggesting that while defringing might be critical for achieving specific science goals, this correction has only a minor effect on the characterization of CCD sensitivity trends correlated with time.

Lastly, we fringe-corrected the observations of the HST standard BD+75D325 observed with the G750M/8561 setting. We show that the defringing tools successfully improve the quality of the science spectrum removing these interference features.

Acknowledgements

Change History for COS(or STIS) ISR YYYY-XX

Version 1: 9 February 2021- Original Document

References

Carlberg, J., 2019, STIS Instrument Science Report 2019-02

Carlberg, J. & Monroe, T., 2017, STIS Instrument Science Report 2017-06

Goudfrooij, P. et al. 1998. STIS Instrument Science Report 98-19

Appendix A

8.1   defringe_TDS.py

```python
from astropy.io import fits
import glob
import matplotlib
matplotlib.use('TkAgg')
import matplotlib.pyplot as plt
import os

cycles = ['cy17_11855',
          'cy18_12411', 'cy19_12772',
          'cy20_13141',
          'cy21_13544', 'cy22_13991',
          'cy23_14423', 'cy24_14829', 'cy25_14970', 'cy26_15558']

for c in cycles:
    print('-'*25)
    print(f'Cycle {c[2:4]}')
    print('-'*25)
    sci_exps = glob.glob(f'test_data/{c}/*_crj.fits')
    for sci_exp in sci_exps:
        targ = fits.getheader(sci_exp.replace('_crj','_raw'),0)['TARGNAME']
        if targ == 'CCDFLAT':
            continue

        sci_main = sci_exp.split('_crj')[0]
        sci_base = sci_exp.split('_crj')[0].split(c[-1]+'/')[1]
        frngflat = f"test_data/{c}/"+
        fits.getheader(sci_exp.replace('_crj', '_raw'),0)['FRNGFLAT'].lower()


        print(f"Science Exposure: {sci_main}")
        print(f"Associated Fringe Flat: {frngflat}")


        ####-------- Begin Fringing process ----------####

        ## normalize fringe flat using normspflat tool
        stistools.defringe.normspflat(f"{frngflat}_raw.fits",
                          f"{frngflat}_nsp.fits", do_cal=True,
                          wavecal=f"{sci_main}_wav.fits")

        ## Flatten the blue end of the flat-field image [ONLY FOR G750L]
        grating = fits.getheader(f"{sci_main}_raw.fits",0)['OPT_ELEM']
        propaper = fits.getheader(f"{sci_main}_raw.fits",0)['PROPAPER']
        if grating == 'G750L':
            with fits.open(f"{frngflat}_nsp.fits") as hdulist:
                hdulist[1].data[:,:250] = 1
                hdulist.writeto(f"{frngflat}_nsp.fits",overwrite=True)
            prod_type = "crj"
        elif grating == 'G750M':
            prod_type = "sx2"

        ## Make fringe flat
        outfile = f"{frngflat}_{sci_base}_frr.fits"
        if os.access(outfile, os.F_OK):
            os.remove(outfile)

        ### E1 aperture needs to extract from a different location
        if 'E1' in propaper:
            stistools.defringe.mkfringeflat(f"{sci_main}_{prod_type}.fits",
                                    f"{frngflat}_nsp.fits",
                                    f"{frngflat}_{sci_base}_frr.fits",
                                    beg_shift=-0.5, end_shift=2.,
                                    shift_step=0.1, beg_scale=0.8,
                                    end_scale=1.7, scale_step=0.04,
                                    extrloc= 894, rms_region=[500,850])
        else:
            stistools.defringe.mkfringeflat(f"{sci_main}_{prod_type}.fits",
                                    f"{frngflat}_nsp.fits",
                                    f"{frngflat}_{sci_base}_frr.fits",
                                    beg_shift=-0.5, end_shift=2.0,
                                    shift_step=0.1,
                                    beg_scale=0.8, end_scale=1.7,
                                    scale_step=0.04)

        ## Defringe science file by dividing by defringed shifted flat
        ## this should create a drj 2D defringe image
        stistools.defringe.defringe(f"{sci_main}_{prod_type}.fits",
                                f"{frngflat}_{sci_base}_frr.fits",
                                overwrite=True)

        ## Extract spectrum from defringed sci exposure (*_dsx1.fits)
```

```
sci_defringed = f"{sci_main}_drj.fits"
out_x1d_defringed = f"{sci_main}_dsx1.fits"

if os.access(out_x1d_defringed, os.F_OK):
    os.remove(out_x1d_defringed)


stistools.x1d.x1d(sci_defringed, output=out_x1d_defringed,
                  verbose=True, trailer=f"{sci_main}_dsx1.trl")


## Plot fringed/defringed spectra
waved = fits.getdata(out_x1d_defringed, 1)['wavelength'][0]
fluxd = fits.getdata(out_x1d_defringed, 1)['flux'][0]

wavef = fits.getdata(f"{sci_main}_sx1.fits",1)['wavelength'][0]
fluxf = fits.getdata(f"{sci_main}_sx1.fits",1)['flux'][0]

plt.plot(wavef, fluxf, 'k', label='Fringed')
plt.plot(waved,fluxd, 'r', label='Defringed')
plt.legend()
plt.title(f"{sci_main}- {propaper}")
plt.xlim(6200,10500)
plt.show(block=False)
input('enter')
plt.savefig(f'{sci_main}_defringed.pdf')
plt.clf()
```