

1 Introduction

This document describes the new UVOT grism wavelength calibration file and possible ways to implement the wavelength calibration using this file. The document also contains a discussion on how to go about using the wavelength calibration, primarily to assist in adapting and testing the calibration software, but it might also be of help for users who want to work with UVOT grism spectra. A separate document intended for inclusion in the calibration documentation will address the accuracy of the calibration.

This version applies only to the *uv* grism nominal wavelength calibration.

The angle of the source to the boresight in the DET coordinate system is used to determine the wavelength anchor point in the first order as well as all the dispersion coefficients and the location of the other orders. The first order wavelengths are determined (expressed as a set of polynomial coefficients) from the pixel coordinate along the rotated spectrum with reference to the anchor point. The wavelength coefficients of additional orders are provided in a similar way. Currently, only the first order has been calibrated, and the second order dispersion information has been provided for development purposes. I have not attempted to make the file format conform in any way to the existing wavelength calibration file format.

2 MSSL Wavelength Calibration File format

The format is FITS. The filename of the file delivered by MSSL is similar to `swwavcal090129_v1_mssl_ug200.fits`. [tbd caldb file name is xxxx] The primary header keywords contain some general information, see the appendix for an example. The first extension includes the data. The data format is a binary table, with columns, each column of dimension 2 in x and y. Each row contains the data for one input angle. The first two columns are for looking up the input angle (in a 2-D (28x28) array; see section 5), the next two columns give the corresponding DETX1ANK and DETY1ANK coordinates of the anchor position in DET – pixel coordinates in the grism detector image. The use of DET – pixel coordinates is explained below.

The fifth column gives the angle θ , which describes the angle of the first order on the detector image near the anchor point. The angle is used for extracting the spectrum and defining the direction for the dispersion polynomial coefficients (see section 5 for more details). The next columns in the binary table contain the first order polynomial coefficients C_{1j} for the dispersion, and column C_{1n} contains the order of the polynomial used for that position. If no solution was found using the automated script (i.e., close to the edges), C_{1n} for that point will have been set to zero, and a default value will have been entered into the C_{1j} coefficients. In future releases, these may be updated by fitting by hand.

The wavelengths can be found from the formula:

$$\lambda = \sum_{j=0,n} C_{1j} p^n$$

With λ the wavelength in Angström, and p the pixel-distance to the anchor point along the direction defined by the angle θ . Similar fields are provided for the second order with coefficients C_{2j} and C_{2j} , where the DETX2ANK, DETY2ANK position provides the point where $\lambda = 2600$ A in second order. The latter can be referenced to the anchor point in the first order, and the rotated spectrum, by using the angle θ to determine its offset from the first order. However, the second order dispersion is referenced to the anchor in first order.

In a future implementation, it may be possible to define the offsets of the second – first order, since in certain detector areas the orders lie partially side-by-side.

Note that the dispersion is *not* defined by following the curvature of the spectrum, see section 5.

There are limitations when the anchor point is too close or even off the edge of the image. It is difficult to predict and interpolate when the anchor point is less than 75 pixels from the edge.

3 Interpolation

The (ϕ_x, ϕ_y) input angles in the wavelength calibration file are on a rectangular grid, allowing the use of bilinear interpolation. (In the accompanying document for the accuracy these are called X_{ϕ_i}, Y_{ϕ_i} .) The bilinear interpolation will only work for dispersion coefficients with the same polynomial order on all the four points. If all four surrounding points do not have the same order dispersion polynomial, I suggest that the `uvotimgism` implementation may either ignore these points, take the closest solution, or solve for all four points the dispersion equation, to get $\lambda(p)$ and then interpolate on the common wavelengths of the four points. The second option (select the closest valid point) should be relatively easy to implement, I think. The latter one will have to exclude points which do not have a valid solution (where $C_{1n} = 0$).

4 The anchor point

The wavelength scale reference point is the 260nm wavelength position in the first order spectrum and is a function of the input angles ϕ_x , and ϕ_y , where the x and y are along the DET X and Y axis.

Inputs

The inputs are:

- 1) the angles ϕ_x , and ϕ_y along the detector X and Y directions of the input-ray of the source with respect to the boresight. The input-ray is the light path before encountering the optical elements, like the filter wheel. In the appendix some examples are worked out for calculating these angles.

- 2) The wavelength calibration file. This file provides a rectangular array of ϕ_x , and ϕ_y angles and corresponding anchor point positions and other parameters.

Outputs

The output is the location of the anchor of the 2600 Å point in the first order spectrum of the source in DET pixel coordinates. The DET pixels coordinates are derived from the DET coordinates (in mm), by using the scale factor 0.009075mm/pix and setting the centre of (0,0) mm to the (1100.5,1100.5) pixel coordinate. This coordinate system is consistent with an intermediate form of the DET system in the TELDEF file. More information is given in the appendix.

Proposed algorithm

Bilinear interpolation can be used to interpolate the input angles. For the calibration I used a smoothing cubic least squares spline fit which gives nearly identical results, so that is not a requirement.

5 The wavelength scale

Inputs

The inputs are:

- 1) The (ϕ_x, ϕ_y) input angle for the source.
- 2) The calibration file.

The *spec* coordinate system used for the wavelength solution

The spectra on the detector exhibit some curvature. In particular in the shortward end of the spectrum the curvature is noticeable, although the long-wavelength part also exhibits some. In addition, the curvature varies over the detector. In order to define a consistent coordinate system in wavelength, the following convention has been adopted:

The slope at the anchor point in first order is determined from the Zemax model prediction across the detector. That slope, θ , is used to rotate the image by $(180-\theta)$, as explained elsewhere. However, θ is also used to define the axis along which the dispersion coefficient and the wavelength scale, have been defined, which I will call the *spec*-coordinate system. The axis *specX* is approximately along the dispersion, and *specY* is normal to the dispersion direction.

The pixel-distance to the anchor point is defined entirely as the coordinate along the *specX* axis. The coordinate increases with increasing wavelength. That means that where the spectrum curves away from the line defined by the anchor and θ , the pixel coordinate is in fact the projected distance along that line and not along the spectrum itself. The pixel coordinate is used for determining the wavelengths in the curved spectrum using the polynomials discussed elsewhere.

Outputs

The output is the polynomial coefficients with respect to the anchor point in the extracted spectrum. If necessary, the anchor point is projected onto the spectrum (i.e., only the

specX coordinate is used.) The unit for the coefficients is in pixels in the *specX* coordinate (i.e., the rotated spectrum). These allow the calculation of the first order wavelength for each pixel along the spectrum using equation 1 in section 4.

6 Proposed processing method and notes

For clarification, I will include a list of steps that closely follow the processing method I have used for the wavelength calibration.

- First determine the source position angle $(\phi_x, \phi_y)_{\text{obs}}$ (see appendix for example on the determination of these angles). Use these to look up the four data points around $(\phi_x, \phi_y)_{\text{obs}}$ in the calibration file and order them so that it is known which ones are smaller/larger in x and y. These are needed for the bilinear interpolation.
- Caution: The grism DET image (e.g., `sw***ugu_dt.img`) when taken from the fits image extension without looking at the header, is actually clipped, so the pixel positions in DET –pixel coordinates can be found by adding (104,78) to the image pixel coordinates. This is important when reading the image extension into IDL or python. (see the `NAXIS1,NAXIS2,CRPIX1,CRPIX2` keywords for the centre, then derive the positions in mm (DET coordinates with centre=(0,0)). The conversion from mm to pixels is in the TELDEF file, 0.009075mm/pix. Using the `uvotapplywcs Ftool`, you will be able to convert the DET(mm) positions to detector pixel coordinates. Alternatively, use the ‘view WCS-d’ coordinate system in the DS9 tool to get the positions.
- All the variables in the table can be found from bilinear interpolation based on the coefficients found from those four input angle data points. In this way, the interpolated anchor position and dispersion coefficients corresponding to the source position are found.
- The interpolated position of the anchor, at 2600A/first order, is in DET – pixel coordinates.
- The detector image of the spectrum (i.e., `sw0034567001ugu_dt.img`) is rotated around the anchor position (`DETX1ANK, DETY1ANK`) by the angle $(180.0-\theta)$ to the *spec* coordinates which were defined in section 5.
- The slice (subimage) of the image around the spectrum (the spectrum image) is extracted. Possibly this can be done after a modification to `uvotimgrism` has been made: The position of the anchor point will be translated into a position in the sliced spectrum image (`specX, specY`); where `specX` is the pixel coordinate of the axis that runs along the spectrum, with its origin at the (projected) anchor point. The actual position of the spectrum is generally offset normal to the dispersion direction by some (<15) pixels from the anchor position. The projection of the anchor onto the actual spectrum defines the wavelength origin for the dispersion solution using the coefficients.
- Note: If the current (2009/02/25) version of `uvotimgrism` needs to be used, that can be done by doing the extraction of the spectrum using the method given by Wayne Landsman (see Appendix D). [*We note here, that we did not modify*

uvotimgrism, and have not any good understanding of the best way to do this to extract the first order spectrum using the anchor point we find. We hope that the next software release can incorporate changes to the tool so it works with this approach.] The image coordinate of the zero order anchor is given by the header keywords CRPIX1,CRPIX2 of the image extension in the extracted spectrum. The distance of the zero order anchor from uvotgraspcorr to the anchor given in this file can be found. All we need to know to use uvotimgrism is the distance from the zeroth order anchor point to the start of the “channels”. (Getting this from the region file, ~ 390 pixels).

- The *specX*-coordinate with units of pixels is used to derive the pixel distance to the wavelength origin. The wavelength is found by applying the polynomial coefficients found by bilinear interpolation above.
- The distance to the 2600A point in second order can be found from θ and the anchor positions in the table, while the second order wavelength scale follows from the *specX* coordinate with reference to the first order anchor. The second order wavelength scale in its current form is primarily useful (from a scientific standpoint) to verify the first-order spectrum for possible second-order contamination; but the main reason to include it, is to make sure we can experiment with how to display the second order location in our quicklook products, with how to include it in output files, and hopefully, having it in the output product will allow us to calibrate the second order.
- A future *zero* order wavelength scale will be referenced to a zero-order anchor point (probably at a different wavelength than 2600A), since a functional fit to the Zemax model wavelengths requires a reference point in the zero order to get good convergence.

7 Test data set

The test data set contains two observations of WR52 near the boresight and three observations of WR86 away from the boresight. The parameters derived using the calibration file are provided in a spreadsheet file. All files are packaged into a compressed tar file, made using `tar -czf uvnominal.tar.gz`, and the same for the testdata sample , and should be self explanatory.

The positions in the spreadsheet are given in pixels on the image with the bottom left corner as the origin. To convert to DET-pixel coordinates (which are those in the calibration file), add [104,78] to them.

8 Concluding remarks

The current version of the calibration file has been tested against the calibration results.

The calibration was based on reading the Zemax model on a grid of field coordinates that are found by rotating and shifting the rectangular grid in angles (ϕ_x, ϕ_y) . Here the field coordinate of a source was derived by rotating and shifting the angle appropriately,

which was followed by a smoothed cubic spline interpolation in the grid of field coordinates. The accuracy of the resulting anchor points was reported in the accompanying UVOT wavelength accuracy document. The calibration file was tested using a bilinear spline and it was found to give the same anchor points as the calibration to within 0.1 pixel, and the same wavelength solution to within a fraction of a pixel.

9 Appendices

Appendix A. Derivation of the input angles for a combined grism & lenticular filter exposure

The angles are derived as follows:

1. Aspect correct the lenticular filter image taken in the same observing sequence as the grism exposure.
2. Use the (header information in) the lenticular filter (pointing) file to derive the position of the source with respect to the boresight (given RA, DEC of the source).

The method used in the calibration is as follows:

```
$> echo "199.2341 12.1234" > radec.txt (write ra,dec to text file)
$> uvotapplywcs infile=radec.txt outfile=skyfits.out
wcsfile="sw0005695004uw1_sk.img[1]" operation=WORLD_TO_PIX'
(make sure to use quotes around the file name with extension – gives sky pixels)
$> acut -f3-4 -d < skyfits.out > skyfits.in (copy the last two numbers into a new file)
$> uvotapplywcs infile=skyfits.in outfile=detmm.txt
wcsfile="sw0005695004uw1_sk.img[1]" operation=PIX_TO_WORLD to=D (DET position in mm)
$> f = open('detmm.txt', "r")
$> x1, y1 = ((f.readline()).split())[2:4] (Copy the last 2 numbers)
$> DETX1ANK,DETY1ANK = (x1,y1)/0.009075+(1100.5,1100.5) (find the anchor position)
```

3. Given the detector coordinates on the lenticular filter image (e.g., *uvw1*) (DETX_ANK_filt,DETY_ANK_filt) of the source, determine the distance to the bore sight in that filter, (DETX_ANK_filt – BORE_X, DETY_ANK_filt – BORE_Y).); here the boresight point (BORE_X,BORE_Y) coordinates have been found from the ones in the TELDEF file by adding (77,77) to convert from RAW to DET-pixel coordinates.
4. Then multiply by the pixel scale (0.502"/pixel/3600) to obtain the angles ϕ_X , and ϕ_Y in degrees.

Appendix B. Derivation of the input angles for a single grism exposure

In this case, use `uvotgraspcorr` to get a better aspect solution for the grism image. Use the updated header keywords (pointing) to derive the source position angles, ϕ_X and ϕ_Y . This can be done by using the transformation of RA, DEC and POINTING to what the detector coordinates DETX, DETY would be in any lenticular filter; then deriving the distance to its bore sight point; and then finding the desired angles by dividing through the lenticular filter pixel scale, which is 0.502"/pixel. This procedure combines aspects of `swiftxform` to go from pointing to sky coordinates and `uvotapplywcs` to get the detector coordinates.

The following roundabout method, using existing uvot ftools, can be used:

1. insert the RA,DEC, *****_PNT** keywords in the header of an arbitrary raw lenticular filter file. Edit the times in the primary and image headers to the times of the grism observation.
 2. Use the attitude file from the grism observation and the appropriate teldef file in:
swiftxform infile=lentimgfile.raw outfile=wcsfile
attfile=attitude_file alignfile= method=AREA to=SKY ra=RA dec=DEC
roll=0.0 teldeffile=\$teldef bitpix=-32 zeronulls=NO aberration=NO
seed=-1956 copyall=NO extempty=YES allempty=NO
 3. Use the steps in Appendix A, with the newly found wcsfile, RA, and DEC.
- The use of the original xform without the intermediate steps to create a wcsfile would possibly be faster, if not cleaner, to do this job.

Appendix C. Sample File headers

```
SIMPLE = T / conforms to FITS standard
BITPIX = 8 / array data type
NAXIS = 0 / number of array dimensions
EXTEND = T
CREATED = 'written by uvotpy.zemax.wrCalFile '
DATE = '2009-02-01'
AUTHOR = 'NPM Kuin (MSSL)'
VERSION = '0.1 '
WHEELPOS= '200 '
FILTER = 'ug200 ' / UV grism Nominal
ORDERS = '12 ' / list of orders included
ROTANGLE= -64.59999999999999 / rotated input phi_x,phi_y by this angle
(deg)
TELESCOP= 'SWIFT ' / Telescope (mission) name
INSTRUME= 'UVOTA ' / Instrument Name
END
```

```
XTENSION= 'BINTABLE' / binary table extension
BITPIX = 8 / array data type
NAXIS = 2 / number of array dimensions
NAXIS1 = 64 / length of dimension 1
NAXIS2 = 784 / length of dimension 2
PCOUNT = 0 / number of group parameters
GCOUNT = 1 / number of groups
TFIELDS = 17 / number of table fields
TTYPER1 = 'phi_xrot'
TFORM1 = 'E '
TUNIT1 = 'deg '
TDIM1 = '(28,28) '
TTYPER2 = 'phi_yrot'
TFORM2 = 'E '
TUNIT2 = 'deg '
TDIM2 = '(28,28) '
```

```

TTYPE3 = 'DETX1ANK'
TFORM3 = 'E'
TUNIT3 = 'pixel'
TDIM3 = '(28,28)'
TTYPE4 = 'DETY1ANK'
TFORM4 = 'E'
TUNIT4 = 'pixel'
TDIM4 = '(28,28)'
TTYPE5 = 'SP1SLOPE'
TFORM5 = 'E'
TUNIT5 = 'deg'
TDIM5 = '(28,28)'
TTYPE6 = 'DISP1_0'
TFORM6 = 'E'
TDIM6 = '(28,28)'
TTYPE7 = 'DISP1_1'
TFORM7 = 'E'
TDIM7 = '(28,28)'
TTYPE8 = 'DISP1_2'
TFORM8 = 'E'
TDIM8 = '(28,28)'
TTYPE9 = 'DISP1_3'
TFORM9 = 'E'
TDIM9 = '(28,28)'
TTYPE10 = 'DISP1_4'
TFORM10 = 'E'
TDIM10 = '(28,28)'
TTYPE11 = 'DISP1_N'
TFORM11 = 'I'
TDIM11 = '(28,28)'
TTYPE12 = 'DETX2ANK'
TFORM12 = 'E'
TUNIT12 = 'pixel'
TDIM12 = '(28,28)'
TTYPE13 = 'DETY2ANK'
TFORM13 = 'E'
TUNIT13 = 'pixel'
TDIM13 = '(28,28)'
TTYPE14 = 'DISP2_0'
TFORM14 = 'E'
TDIM14 = '(28,28)'
TTYPE15 = 'DISP2_1'
TFORM15 = 'E'
TDIM15 = '(28,28)'
TTYPE16 = 'DISP2_2'
TFORM16 = 'E'
TDIM16 = '(28,28)'
TTYPE17 = 'DISP2_N'
TFORM17 = 'I'
TDIM17 = '(28,28)'
VERSION = '0.1'
CREATED = 'N.P.M. Kuin (MSSL) 2009-02-01'
EXTNAME = 'WAVCALUGRISM200'
HISTORY when no dispersion solution, DISP?_N set to zero
END

```

The pixel coordinate in DET coordinates with centre 1100.5,1100.5 and scale factor 0.5496"/pixel

Appendix D. The reduction of a grism spectrum with existing tools.

This appendix has been included for helping users reduce grism spectra using the currently available tools, which can be improved using the new wavelength calibration using appendix A. The calculation of where the anchor position lies in the extracted uvotgrism spectrum is difficult at the present moment since the distance to the start of the channels in the uvotgrism output file is not in the header.

These are instructions from Wayne Landsman for obtaining a quicklook grism spectrum. I use GRB081203 as an example, and discuss only currently (Jan 2009) available tools.

1. Get the grism distortion file

The grism images are not aspect corrected in the pipeline. The current software release includes a task `uvotgraspcorr` to perform the aspect correction, but it requires a grism distortion file which is not yet in the CALDB. This file – if you don't already have it -- can be downloaded from

<http://idlastro.gsfc.nasa.gov/ftp/landsman/grismdistort/swugrdist20041120v903.fits>

As further described below, the `distfile` parameter of `uvotgraspcorr` should point to this distortion file.

2. Obtain the grism detector (`_dt`) image. (`sw00336489000ugu_dt.img.gz`)

This product is routinely created by the pipeline for grism images (though not for the lenticular filters). Note that when obtaining archival images using Browse, only the raw and sky images are displayed, but the detector images should be available in the `uvot/image` directory.

3. Aspect correct the detector image:

```
>gzip -d sw00336489000ugu_dt.img.gz  
>uvotgraspcorr sw00336489000ugu_dt.img distfile=swugrdist20041120v903.fits  
catspec=usnob1.spec
```

The catalog descriptor file `usnob1.spec` is the same one used to aspect correct the lenticular images, e.g. from

http://heasarc.gsfc.nasa.gov/docs/swift/analysis/threads/uvot_thread_aspcorr.html

The detector image must be uncompressed before using `uvotgraspcorr`. Besides correcting the aspect solution, `uvotgraspcorr` also models the grism-specific distortion by including cubic astrometric terms in the FITS header (using the "SIP" convention -- see

<http://ssc.spitzer.caltech.edu/postbcd/doc/shupeADASS.pdf>). The reason the distortion is modeled rather than removed is that the very long first order spectra do not follow the same distortion pattern as the zero-orders used to define the astrometry.

One can determine if a grism detector image has been successfully aspect corrected by examining if the ASPCORR keyword in the FITS header is set to "GRASPCORR".

4. [OPTIONAL] Examine the image and spectrum to identify possible problems.

(a) First use UVOTAPPLYWCS to convert the RA (=233.03158) and Dec (=63.52081) to detector coordinates.

```
>uvotapplywcs pos.dat out.dat sw00336489000ugu_dt.img operation=WORLD_TO_PIX from=S
```

The input file pos.dat contains the RA and Dec and the detector position (1367.18 724.08) is given in the output file out.dat.

(b) Examine the image with DS9 (or IDL or Aladin...)

```
ds9 sw00336489000ugu_dt.img[1] -regions src.reg
```

where the region file needs to include the use of alternate WCS coordinates.

```
global color=green font="helvetica 10 normal" select=1 highlite=1 include=1 source  
wcss;fk5  
circle(15:32:7.598, +63:31:14.82, 5") # color=red
```

The astrometric information in the detector image is not stored in the primary WCS (world coordinate system) keywords but in alternate 'S' (Sky) keywords, so one may need to set DS9 to use 'S' coordinates under the multiple world coordinates (WCS) button. Note that the recognition of alternate sky coordinates works in the current version of DS9 (V5.4) but may not work in older (V4) versions. I like to use histogram equalization, with zoom set to 1/2. With the above region file, the GRB zero-order should indicated with a circle. Check whether the GRB spectrum is contaminated by any unrelated spectra (not for GRB081203). Overlay a star catalog to see if there is any contamination by stars (for GRB081203 there is a field star which falls on the 4900 A region.)

5. Extract a spectrum from the detector image we use the FTool uvotimgrism.

```
uvotimgrism infile=sw00336489000ugu_dt.img+1 outfile=sw00057000002ugu_1.pha ang=151.6  
backfile=sw00057000002ugu_1_back.pha badpixfile=NONE wavefile=CALDB areafile=CALDB  
teldeffile=CALDB ra=233.03167 dec=63.520778 srcwid=15
```

This tool uses the supplied RA and Dec to locate the zero order, and then extracts the first order spectrum.

1. There is hardcoded value of ang (=151.4, the angle of the first-order from the obsolete) which is obsolete -- it was determined before uvotgraspcorr was developed. The value of 151.6 is usually best.
2. The absolute calibration was determined using a source width for the extraction slit of 21 pixels. To improve the S/N of this faint spectrum we need to use an optimised extraction width.
3. The absolute calibration is currently only available for the wavelength range of 1700 - 4900 A. You may see error messages about being unable to calibrate wavelengths outside this region. However, the grism has little sensitivity outside this range anyway.
4. uvotimgrism creates a region file, e.g. sw00336489000ugu_dt.img.reg, which can be used with DS9 to display the extraction and background regions used. If these are not satisfactory (e.g. there is a contaminating source in the background) then one can call uvotimgrism again adjusting the values of bkgoff1, bkgwid1 giving the offset and width of the lower background extraction slit, or bkgoff2, bkgwid2 giving the offset and width of the upper background extraction slit.

Further reduction notes:

a) The .pha file created by uvotimgrism contains 3 extensions. The first (SPECTRUM) stores the spectrum in counts and is meant for use with XSPEC. The second (CALSPEC) extension stores information about the spectrum including the wavelength (FITS column LAMBDA), absolutely calibrated flux (FLUX), and error (FLUX_ERR). This extension can be interrogated with FITSIO tools to obtain a reduced spectrum. The third (IMAGE) extension contains a subimage including the zero and first order rotated so that the dispersion direction is (roughly) along the X axis. One can view these spectra with your favorite tool (e.g. FV, IDL, IRAF).

b) XSPEC. The reduction recipe was only for the quicklook analysis (i.e. the first GCN) and so did not discuss XSPEC which presumably should only be done after we have carefully reduced both the XRT and UVOT data.

Use of uvotrmfgen: it creates a proper response matrix based on the grism effective area and PSF, for use with XSPEC. Currently there is only one single value for the calibration, but in the future the variation of the response over the detector will be mapped out and then can be used to create a response matrix for each observation using this tool.