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WFPC2 DATA ANALYSIS
A Tutorial

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Introduction

This document is an introduction to basic data reduction and analysis for the Hubble Space Telescope's Wide Field and Planetary Camera (WFPC2), written specifically for people unfamiliar with WFPC2 data. It has been written as a tutorial, and you are encouraged to retrieve the suggested datasets and try the examples in this document. However, before proceeding, you should have:

- some familiarity with IRAF,
- the current version of IRAF and STSDAS installed on your workstation,
- the current version of STARVIEW (the software interface to the HST archive) installed on your workstation,
- an account on the HST Data Archive at STScI.

More information about IRAF, STSDAS, and the HST Data Archive at STScI can be found at these websites:

- IRAF: http://iraf.tuc.noao.edu/
- STSDAS: http://stsdas.stsci.edu/STSDAS.html
- HST Data Archive: http://archive.stsci.edu/
- StarView Software: http://starview.stsci.edu/

Useful documents to have in hand while going through the exercises in this tutorial are:

- The HST Data Handbook for WFPC2 (v4.0 or higher)

  http://www.stsci.edu/hst/HST_overview/documents/datahandbook/

- The WFPC2 Instrument Handbook (v6.1 or higher)

  http://www.stsci.edu/instruments/wfpc2/Wfpc2_hand/wfpc2_handbook.html

- STSDAS Users Guide

  http://stsdas.stsci.edu/Document3.html

Other useful documents for your WFPC2 library are:

- The 1997 HST Calibration Workshop with a New Generation of Instruments, September 22-24, 1997.

  http://www.stsci.edu/stsci/meetings/cal97/proceedings.html

- Calibrating Hubble Space Telescope: Post Servicing Mission, a Workshop held on May 15 - 17, 1995.

  http://www.stsci.edu/ftp/instrument_news/WFPC2/Wfpc2_serv/post_serv.html

- A Field Guide to WFPC2 Image Anomalies by J. Biretta, et al.

  http://www.stsci.edu/instruments/wfpc2/Wfpc2_anom/wfpc2_anomalies.html

- Performance & Calibration of WFPC2 on the Hubble Space Telescope, Jon Holtzman, et al. Link available at:

  http://www.stsci.edu/instruments/wfpc2/wfpc2_doc.html#Stat

- The Photometric Performance and Calibration of WFPC2, Jon Holtzman, et al. Link available at

  http://www.stsci.edu/instruments/wfpc2/wfpc2_doc.html#Phot

- Synphot Users Guide

  http://stsdas.stsci.edu/Document3.html

A paper copy of most of these documents can be requested by sending e-mail to help@stsci.edu. Regular updates are posted on the WFPC2 website (check the "ADVISORIES" page) at http://www.stsci.edu/instruments/wfpc2/wfpc2_top.html.

Regular WFPC2 users may wish to subscribe to the Space Telescope Analysis Newsletter for WFPC2, which is circulated several times a year. To subscribe, send a message to listserv@stsci.edu with the "Subject:" line blank and the following in the body "subscribe wfpc_news <YOUR NAME>".

On-line help files are also available in IRAF and STSDAS. The task *apropos* allows you to find an IRAF or STSDAS task. For example, to find out how to access the task *crrej*, just type:

```
apropos crrej
```

apropos will return a list of tasks that have the string "crrej" in the task title or description, along with a brief description and its location in IRAF or STSDAS.

```
apropos crrej
```

sky - Sky processing by "crrej-like" algorithm. (stsdas.analysis.dither)
ocrreject - Generate a STIS CCD image (images and spectra) free of (stsdas.hst_calib.stis)
crrej - Combine images to make a cosmic ray free image. (stsdas.hst_calib.wfpc)

In this example, the task *crrej* can be obtained by loading the packages *stsdas*, *hst_calib*, and *wfpc*.

If you need detailed information about a particular IRAF or STSDAS task, type *help* <taskname>. For example.

```
help crrej
```

To write the *crrej* on-line help to a file, type

```
help crrej | type dev=text > crrej.help
```

To see examples of how to run a particular IRAF or STSDAS task, type "examples <taskname>". For instance,

```
examples crrej
```

This document is divided into four sections:

- **SECTION 1** provides a brief introduction to the Multimission Data Archive at Space Telescope (MAST) and an example of how to retrieve HST WFPC2 data using StarView.
- **SECTION 2** covers useful IRAF and STSDAS image analysis tasks.
- **SECTION 3** has an overview of the calibration pipeline, and how to recalibrate WFPC2 data.
- **SECTION 4** is a guide to WFPC2 photometry using the *noao.digiphot.apphot* package.

Throughout this document, most examples will use the following datasets from program 8134, visit 7:

- F555W: u5ay0701r, u5ay0702r (exposure 10 in visit 7)
- F814W: u5ay0704r, u5ay0705r (exposure 30 in visit 7)

In addition, the following datasets will be used for specific sections:

- For demonstrating how to fix a bias jump: u3b10602t
- For demonstrating contamination corrections for UV images: u6hidg01m, u6hidg02m, u6hidg03m, u6hidg04m, u6hidg08m

For general questions about WFPC2 data reduction, please send e-mail to help@stsci.edu. For questions and comments about this document, please contact Shireen Gonzaga (shireen@stsci.edu) or Anton Koekemoer (koekemoe@stsci.edu).

1. An Introduction to the Hubble Data Archive

HST data is archived at three sites:

- Hubble Data Archive at STScI's Multimission Archive (http://archive.stsci.edu/)
- Canadian Astronomy Data Center (http://cadcwww.dao.nrc.ca/hst/)
- Space Telescope European Coordinating Facility (http://archive.eso.org/archive/hst/)

This section deals only with the Hubble Data Archive at STScI's Multimission Archive (MAST). To retrieve data from the CADC or ST-ECF archives, please refer to instructions on their respective websites.

HST science data taken by a principal investigator remain proprietary to that investigator for some period of time, typically a year. After the proprietary period expires, anyone who registers for an account to access the HST archive will be able to retrieve that data. Registrants are issued an account username and password. To register, go to http://archive.stsci.edu/registration.html or contact archive@stsci.edu.

There are two ways to search and retrieve HST data from the Hubble Data Archive: One is "StarView," a Java-based database and search tool for finding and retrieving data, and it is particularly useful to people who require specialized search tools. StarView can be installed and run on the user's machine. Details on how to do this are available at http://starview.stsci.edu/. The other method, one that suits the needs of most people, is via an easy-to-use web interface search form at http://archive.stsci.edu/cgi-bin/hst/.

After datasets of interest are found, they can be "marked" for retrieval in StarView or in the data archive web interface search form. The data can either be deposited at an archive "pick-up" site to be transferred via FTP to the user's home machine, or sent directly to the user's home machine (a username and password for the destination machine must be provided at the time of the request). The user will be notified via e-mail when the data has been retrieved.

A note about StarView searches and retrievals: StarView has many search options available to the user. The "Searches" pull-down menu in the main StarView menu will allow you to select and display the appropriate search form. Enter your search parameters in the top table-like portion of the form, then click the "Search" button. To retrieve the search results, you can "Mark" the displayed results for retrieval, click the "Submit" button, and follow the subsequent instructions for data retrieval. More adventurous users may also wish to build customized queries using StarView.

- All WFPC2 data is processed by On-the-fly Reprocessing, which ensures that the data is calibrated with the best- and latest-available calibration reference files at the time of a user’s request. Each dataset consists of one of the following types of files:
- "raw" or uncalibrated data files
- calibrated data files
- data quality files (information about the positions and characteristics of bad pixels)
- jitter files (information about telescope guiding during the observation, an optional request)

These different types of files will be covered in more detail later in this tutorial.

2. Working with WFPC2 Images

IRAF tasks are found in "packages." A package contains several tasks that share a common trait. For instance, tasks specific to WFPC2 are found in the *wfpc* package. Packages are hierarchical, that is, a package can be found within a package. For instance, the *wfpc* package is found in the *hst_calib* package, which is found in the *stsdas* package which in turn is a top-level package in IRAF.

Before using a task, be sure to load the package that contains that task, or else, IRAF will not recognize your command. If a task is used often, its package name may be entered in the IRAF start-up file, called either "login.cl" or "loginuser.cl," found in your IRAF home director. That way, the package is automatically loaded whenever you start IRAF. (To start IRAF, go to your IRAF home directory and type **cl**, then hit <return>.)

Some useful packages to load for this tutorial, or to enter into your IRAF startup file, are listed below. To load a package, simply type the package name at the *cl* prompt, then hit <return>.

images	*(*a top level package in IRAF)
tv	(a package within the *images* package)

stsdas	(a top-level package in IRAF)
fitsio	(a package in the *stsdas* package)
hst_calib	(a package in the *stsdas* package)
wfpc	(a package in the *hst_calib* package)
toolbox	(a package in the *stsdas* package)
ttools	(a package in the *toolbox* package)

If you are running IRAF on a Sparcstation, be sure to run it in an xterm window or some of the tasks mentioned in this chapter, such as *imexamine*, will not work. If you have problems, please consult your local IRAF expert or systems administrator.

2.1 Data Formats

FITS (Flexible Image Transport System) is a standard format for storing and exchanging astronomical information that is used world-wide. GEIS files (Generic Edited Information Sets) is the data format used by STSDAS for older HST instruments including WFPC2.

For instruments like WFPC2 that use the GEIS format, their data files are delivered from the archive to the user as "waivered FITS" files. The more recent instruments like STIS and NICMOS use a different flavor of FITS called "extension FITS," to take advantage of recent capabilities added to the FITS format.

There are future plans to convert all WFPC2 waivered FITS files to extension FITS files to make their data structures similar to that of the newer instruments. But until then, all WFPC2 waivered FITS files must be converted to the GEIS format for use in IRAF and STSDAS. For more information about these file formats, please refer to the HST Data Handbook section called "Introduction," available at
http://www.stsci.edu/hst/HST_overview/documents/datahandbook/.

An IRAF format image has two components. One is called a header file (it has the extension ".imh") where information about the observation, such as date, filter, and mode are stored. The second component is called the data file (with the ".imd" extension), a binary type file containing the actual image. GEIS data files are similar to IRAF format files. However, the GEIS format is designed to accommodate several images within a single dataset. This is a required feature for WFPC2, where a single observation is represented by four separate images, each taken by one of the four CCD chips.

How do I Convert a WFPC2 Image from FITS to GEIS format?

Before doing this conversion, two important IRAF/STSDAS parameters must be set. This can be done whenever you work with WFPC2 images in STSDAS, or you can make it a default setting by editing your login.cl or loginuser.cl file located in your IRAF directory.

1. Set your default image type in IRAF to the GEIS format (the standard default in IRAF is "imh").

   ```
   set imtype = hhh
   ```

2. Set your image display software to display 800x800 pixels, the dimensions of a single WFPC2 chip (the default IRAF dimensions are imt512).

   ```
   set stdimage = imt800
   ```

The conversion from waivered FITS to GEIS is done using the STSDAS task *strfits*; Be sure to set the parameters *xdimtog=yes* and *oldirafname=yes*. Here’s an example of the *strfits* parameter file for converting FITS files on disk to GEIS files:

```
PACKAGE = tables.fitsio
TASK = strfits

fits_files = "*.fits"          FITS data source
file_list = ""                 File list
iraf_files = ""                IRAF filename
(template = "none")            template filename
(long_header = no)             Print FITS header cards?
(short_header = yes)           Print short header?
(datatype = "default")         IRAF data type
(blank = 0.)                   Blank value
(scale = yes)                  Scale the data?
(xdimtogf = yes)               Transform xdim FITS to multigroup?
(oldirafname = yes)            Use old IRAF name in place of iraf_file?
(force = no)                   Force conversion from fits?
(offset = 0)                   Tape file offset
(Version = "2-Aug-2000")       Strfits version
(mode = "ql")
```

Before running *strfits*, make sure that your "hidden" parameters are set properly (hidden parameters are the parameters in parenthesis). If you wish to change the default values of the hidden parameters in your task, use the IRAF task *epar*. Or you can explicitly set them in the command line when you run *strfits* (see the second line of the example below).

To convert all FITS files in the current directory to GEIS

```
strfits *.fits "" ""
```

or

```
strfits *.fits "" "" xdimtogf=yes oldirafname=yes
```

The two double quotes in the examples above mean that default values were used for the parameters *file_list* and *iraf_files*. If you wish to only convert a few select files in your directory from FITS to GEIS, you can give *strfits* a list of files to be converted (in this example, listed in the file "list").

```
strfits @list "" ""
```

2.2 Displaying WFPC2 Images

There are two commonly-used image display tools: *saoimage* and *ximtool*. *saoimage* can be started simply by typing **saoimage &** on your workstation xterm or console window (the *&* runs it as a background job).

For *ximtool*, type **ximtool &**

Choosing which tool to use is a matter of personal preference. Try both tools and pick the one that best serves your needs.

To display an image from IRAF, open either *ximtool* or *saoimage*. Use the task *display* to display the image on your image display tool. Remember that WFPC2 GEIS-format images have up to four images that can be displayed, each representing an image from either the PC, WF2, WF3, or WF4. When displaying an image, a group must be specified.

In this example, group 2 of image u5ay0701r.c0h is displayed (in the first image frame for *ximtool*).

```
display u5ay0701r.c0h[2] 1
```

Try playing with the contrast and color tables in *saoimage* or *ximtool*. Also try editing the *display* parameters. You could set the lower and upper image display ranges, *z1* and *z2*, to different values. (If you manually set *z1* and *z2*, be sure to set the parameters *zrange* and *zscale* to **"***no"* or as illustrated in the example below, *"zr- zs-"*.)

Example:

```
display u5ay0701r.c0h[2]  1 zr- zs- z1=-5 z2=200
```

If you are viewing an object with low surface brightness, such as a galaxy, try changing the parameter *ztrans* from *linear* (the default value) to *log*.

Example:

```
display u5ay0701r.c0h[2]  1 zr- zs- z1=-5 z2=200 ztrans=log
```

“Blinking” Two or More Images with the Same Pointing If you wish to visually compare two images, for instance, u5ay0701r.c0h and u5ay0702r.c0h, display each image in separate image display buffers and “blink” them.

In *saoimage*, display the first image. Select *scale*, then select the *blink* button with the left-most mouse button to store the image in an image buffer. Next, display the second image. Making sure that the *scale* button is highlighted, place the cursor on the image, and press the left-most button. This will allow you to view the previous image again, and you can blink back and forth between the two images by clicking that button. Similarly, a second image can be stored in another buffer by clicking on the middle mouse button, and a third by clicking on the right-most mouse button. Therefore, it is possible to “blink” four images with *saoimage*, using the left, middle, and right buttons. (Note: this method works on UNIX Sparcstations. For PCs running Linux, and Macs running OSX, please check the SaoImage website at http://tdc-www.harvard.edu/software/saoimage.html for information on using an alternate tool called DS9.)

In *ximtool*, four frames are available for display, one at a time, by specifying which frame to use in the *display* task. Use the *blink* button in the menu to toggle between the images. In the example below, group 2 of the image will be displayed in frame 3 of *ximtool*.

```
display u5ay0701r.c0h[2]  3
```

2.3 Getting More Information about the WFPC2 Images

Information about the images are available from two sources:

- the Phase2 proposal
- image header keywords

2.3.1 Looking at the Original Phase2 Proposal

Phase 2 proposals can be viewed at

http://presto.stsci.edu/public/propinfo.html

Enter the four-digit program ID (no leading zero in the number) in the "Get Proposal Information" field. The datasets used in this document come from program 8134. A screen containing program information will appear. Select the "formatted listing" button to view the program. Increase the size of the screen so the entire width of the display can be easily read.

2.3.2 Reading the Image Header File

In this section, we will take a close look at the calibrated data header file (with extension .c0h) for dataset u5ay0701r. The header file is populated with keywords containing information about the observation. Keyword definitions can be found in the WFPC2 Data Handbook, located at http://www.stsci.edu/hst/HST_overview/documents/datahandbook/.

There are several ways to look up information about an image in its header file. But first, view the header file using a paging command (like *more* in UNIX systems) or an editor (like *vi* or *emacs* in UNIX systems). You will see keywords common to all groups in a dataset, and pointers to group-dependent keywords that are stored in the group binary data file.

- The STSDAS task *iminfo* gives a summary of important parameters for a dataset.

  iminfo u5ay0701r.c0h

```
Rootname        Instrument          Target Name
u5ay0701r       WFPC2               NGC2100

Program        = 5ay            Obs Date       = 1999-10-13
Observation set = 07            Proposal ID= 8134
Observation    = 01             Exposure ID = 07-010
Source         = Unknown        Right ascension = 5:42:08.4
File Type      = SCI            Declination    = -69:12:41
Equinox        = J2000

First filtername = F555W Number of groups = 4
Second filtername =             Data type      = real

Image type      = EXT           Exposure time (sec)    = 350.
Mode            = FULL          Dark time (sec)        = 350.
Serials         = OFF
Shutter         = B             Calibration steps done:
Kelsall spot lamp = OFF         MASK ATOD BLEV BIAS DARK FLAT
```

- The STSDAS task *imheader* displays all header keywords in a group (this also includes group-dependent keywords that are “hidden” in the binary group image file).

  imheader u5ay0701r.c0h[2] l+ | page

  The *l+* option tells *imheader* to display all keywords for group 2. Specifying *l-* will display only a few major keywords in the header file. *page* is an IRAF (also UNIX) command that will allow you to scroll through the information. (The | symbol simply pipes the output to the command *page*.)

- If you know the keywords you wish to look up, try *hedit*. The example below illustrates how values for the keywords DETECTOR and BIASODD in the image u5ay0701r.c0h[2] are obtained.

```
hedit u5ay0701r.c0h[2] DETECTOR,BIASODD .
```

```
u5ay0701r.c0h[2],DETECTOR = 2
u5ay0701r.c0h[2],BIASODD = 353.7735
```

(Note: The period after BIASODD is not a typo. It tells *hedit* not to change the keyword value.)

- Another task that displays keyword values is *hselect*. Here, we look up the keyword values DETECTOR, BIASODD, and BIASEVEN for group 3 (WF3 chip) of all images in the directory. *$I* echoes the dataset name in the results.

```
hselect *.c0h[3] $I,detector,biasodd,biaseven yes
```

```
u5ay0701r.c0h[3]   3    305.3148  305.3178
u5ay0702r.c0h[3]   3    305.575   305.5302
u5ay0703r.c0h[3]   3    305.5299  305.5027
```

Some Useful WFPC2 Header Keywords

DETECTOR CCD chip used to obtain image; 1 for PC, 2 for WF2, 3 for WF3, and 4 for WF4. A group-dependent keyword.

DATE-OBS Date of observation.

TIME-OBS Time of observation in Universal Time

FILTNAM1 Spectral element used in observation.

FILTNAM2 Second spectral element (if any) used in observation

EXPTIME Exposure time

FGSLOCK Type of guiding, either FINE (fine lock) or GYRO (gyro control)

EXPFLAG Indicates if the exposure was interrupted (like loss of lock on guide stars)

PROPOSID Phase 2 proposal ID

LINENUM Visit and line number of exposure in the phase 2 proposal

CRPIX1 *x* coordinate of reference pixel. Group-dependent keyword.

CRPIX2 *y* coordinate of reference pixel. Group-dependent keyword.

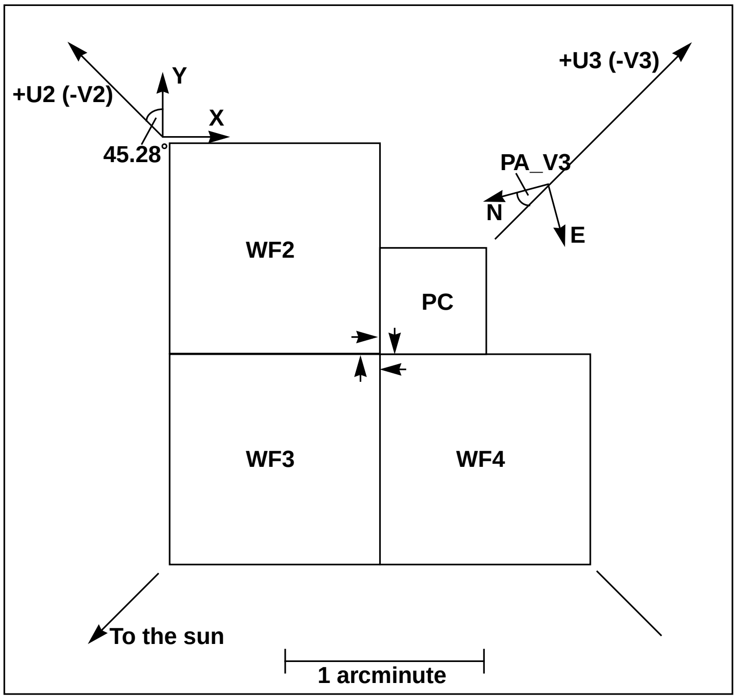
CRVAL1 Right ascension of reference pixel (in degrees). Group-dependent keyword.

CRVAL2 Declination of reference pixel (in degrees). Group-dependent keyword.

ORIENTAT The angle (in degrees) between a chip's positive y-axis and celestial north. The angle values ranges from -180 degrees to 180 degrees, where a positive angle is measured clockwise, and a negative angle is measured counter-clockwise. Group-dependent keyword.

PA_V3: The angle in degrees, measured north to east, between celestial north and the positive V3 axis of the telescope. (The same value applies to all four chips because PA_V3 is defined in the spacecraft frame of reference.)

Figure 1: A diagram of the WFPC2 field-of-view, with the V2 and V3 axis directions. The arrows at the center indicate the readout directions for each chip.



2.4 Useful WFPC2 Data Reduction and Analysis Tasks

Listed below are some frequently-used IRAF and STSDAS tasks:

imexamine	Examine images using image display, graphics, and text (*cl.images.tv*)
wstatistics	Compute & print WF/PC image pixel statistics. (stsdas.hst_calib.wfpc)
cursors	Save a plot displayed on the graphics window to a postscript file. (*cl.language*)
compass	Draw north and east arrows (*stsdas.graphics.sdisplay*)
xy2rd	Translate a 2-D image pixel coordinate to right ascension and declination (*stsdas.toolbox.imgtools*)
rd2xy	Translate right ascension and declination to 2-D image pixel coordinates. (*stsdas.toolbox.imgtools*)
metric	Translate WF/PC pixel coordinates to RA & Dec with geometric distortion correction. (*stsdas.hst_calib.wfpc*)
invmetric	Translate WF/PC pixel coordinates to RA & Dec with geometric distortion (*stsdas.hst_calib.wfpc*)
wmosaic	Mosaic the four WF/PC frames into one image. (*stsdas.hst_calib.wfpc*)
crrej	Combine images to make a cosmic ray free image. (*stsdas.hst_calib.wfpc*)
imedit	Examine and edit pixels in images (*cl.images.tv*)
wfixup	Interpolate over bad columns in a WF/PC frame. (*stsdas.hst_calib.wfpc*)
synphot	Tasks for synthetic photometry and modelling instrument response. (*stsdas.hst_calib*)

2.4.1 *imexamine* - Examine images using display, graphics. (*cl.images.tv*)

imexamine (which can also be typed as *imexam*) is a useful task for detailed examination of features in images. Highlighted below are several particularly useful features:

- First, display the image using the *display* task
- In your IRAF window, type

```
imexam
```

- A cursor will appear on the image. Place the cursor on a star and hit **s**. A three-dimensional plot of the star will appear on a graphics window.
- Place the cursor on a star and hit **r**. A radial plot of the star appears on the graphics window.
- Place the cursor on a star and hit **a**. No plot appears but x,y coordinates of the star’s center, and other useful information appears on the screen where *imexam* is being run.
- To try other *imexam* features, type **?** on the image for help. There are lots of other features to play with!
- To exit from *imexam*, place the cursor on the image and type **q**.
- More information can be found in the *imexam* on-line help file, accessed by typing **help imexam**.

2.4.2 *wstatistics* - Compute & print WF/PC image pixel statistics. (*stsdas.hst_calib.wfpc*)

wstatistics (which can also be typed as *wstat*) is used to obtain pixel value statistics of images. Quantities such as minimum, maximum, mean, standard deviation, midpoint, mode, skew and kurtosis can be computed for an image or image section. This task can also be used with the image data quality file to exclude bad pixels. The data quality pixels to include or exclude from the statistics calculations can be set by the parameter set *dqfpar* (this is a sub-task that is called by *wstatistics*).

Get the image statistics for a central 100x100 pixel region in all four chips for image *u5ay0702r.c0h*. Use the data quality file to exclude all flagged pixels except fixed hot pixels.

```
wstat u5ay0702r.c0h[300:500,300:500] usedqf=yes fixhpbit=no
```

```
# Image statistics for ’u5ay0702r.c0h[300:500,300:500]’ with mask
’u5ay0702r.c1h[300:500,300:500]’
GROUP   NPIX    MIN  MAX    MEAN     MIDPT   MODE    STDDEV
1       39380   2.   3631.  70.7413  20.024  9.926   228.34
2       38700   1.   3788.  16.2294  7.0824  5.8933  82.545
3       39268   0.   3725.  10.3828  5.7367  5.123   52.823
4       38672   1.   3535.  11.2648  5.9741  4.8385  58.486
```

2.4.3 *cursors* - Save a plot displayed on the graphics window to a postscript file. (*cl.language*)

If you're interested in saving a particularly interesting plot to a file, try this:

- Exit from *imexam* or any other task that was used to generate the plot, with the plot of interest still displayed on the graphics window.
- In the same IRAF window, type **=gcur**
- type **:.write filename** to create a metacode file called "filename." The text will appear in the graphics window.
- Hit **<return>** to exit from the *cursors* mode
- Convert the metacode file to a postscript file by typing

```
psikern filename device=psi_defm out=filename.ps
```

- You can now display that postscript file with the *ghostview* or *gview* tool in UNIX or other postscript-viewing tool.

More information about using the *cursors* tool can be found by typing

```
help cursors
```

2.4.4 *compass* - Draw north and east arrows. (*stsdas.graphics.sdisplay*)

The *compass* task is used to draw arrows pointing to the north and east on the image.

Create a copy of u5ay0701r.c0h[2] called outimage.hhh that has an arrow drawn to show “North" at the position (400,400).

```
compass u5ay0701r.c0h[2] outimage.hhh  400 400
```

2.4.5 *xy2rd* - Translate 2-D image pixel coordinates to right ascension and declination. (*stsdas.toolbox.imgtools*)

This task converts the x-y pixel position to Right Ascension and Declination. *xy2rd* uses the group parameters *CRVAL1*, *CRVAL2*, *CRPIX1*, *CRPIX2*, and other coordinate-related keywords to extrapolate the RA and Dec values.

Find the RA and Dec at the coordinate (400,400) in WF4 in hours, minutes, and seconds:

```
xy2rd u5ay0701r.c0h[4] 400 400 hms=yes
RA = 5:42:08.6422, Dec = -69:13:35.784
```

Note: the values are approximate because no geometric distortion correction is used by this task.

2.4.6 *rd2xy* - Translate right ascension and declination to 2-D image pixel coordinates. (*stsdas.toolbox.imgtools*)

rd2xy is the opposite of *xy2rd*. For example, find the position, in image pixel coordinates, for RA = 5:42:08.6422, Dec = -69:13:35.784 for image u5ay0701r.c0h[4].

```
rd2xy u5ay0701r.c0h[4] 5:42:08.6422 -69:13:35.784 hour=yes
```

```
X =   400.00, Y =   400.00
```

Note: the values are approximate because no geometric distortion correction is used by this task. The values could be off by several pixels at the corners.

2.4.7 *metric* - Translate WF/PC pixel coordinates to RA & Dec with geometric distortion (*stsdas.hst_calib.wfpc*)

Like *xy2rd*, this task translates x-y pixel values to right ascension and declination, but takes the extra step of applying geometric corrections and optional centroiding. The WF2 values for CRVAL1, CRVAL2, CRPIX1, CRPIX2, and other coordinate-related keywords are used as a reference point for measurements in all chips within a dataset. Therefore, if WF2 data is not present in the dataset (as is possible for single-chip readouts), this task will not work. Note: whenever possible, use *metric* instead of *xy2rd* because *xy2rd* does not take geometric distortion into account.

```
metric u5ay0701r.c0h[4] 400 400 hms=yes centroid=no
```

```
# METRIC version: 2.1 (Jun 1995)
# input file: u5ay0701r.c0h[4]
# centroid box size = 7 pixels
#x(raw)  y(raw) x(cent) y(cent) x(geom) y(geom) x(meta) y(meta)    RA         Dec
  400.00    400.00    400.00    400.00    400.00    400.00  -298.24  -330.75  5:42:08.6368
-69:13:35.749
```

2.4.8 *invmetric* - Translate WF/PC pixel coordinates to RA & Dec with geometric distortion (*stsdas.hst_calib.wfpc*)

This task does the inverse of *metric*, taking input RA and Dec values for an object (or a table of RA and Dec values). The result is the object's x,y pixel position and chip number.

```
invmetric u5ay0701r.c0h "5:42:08.6368" "-69:13:35.749"
```

```
# INVMETRIC version: 2.1 (Jun 1995)
# input file: u5ay0701r.c0h
#     RA          Dec          X       Y     chip
5:42:08.6368 -69:13:35.749  400.00  400.00    4
```

2.4.9 *wmosaic* - Mosaic the four WF/PC frames into one image. (*stsdas.hst_calib.wfpc*)

The four groups in a WFPC2 science dataset can be quilted together to form a 1600x1600 pixel image using the task *wmosaic* located in *stsdas.hst_calib.wfpc*.

In order to display the entire mosaic'd image, be sure to type

```
set stdimage = imt1600
```

This task will correct for geometric distortion in each chip, as well as rotation, offsets, and scale differences among the chips.

Example:

```
wmosaic u5ay0701r.c0h u5ay0701r_mos.hhh
```

2.4.10 *crrej* - Combine images to make a cosmic ray free image. (*stsdas.hst_calib.wfpc*)

WFPC2 images are undersampled, making it difficult to distinguish between faint stars and low energy cosmic rays, particularly for long exposures that accumulate many hits. One cosmic ray removal strategy is to take multiple exposures at the same pointing, combine the images, and reject high counts that occur at the same position in only a few of the frames (indicating a cosmic ray). Note: this will not remove hot pixels because they remain in the same location in each input image with the same pointing. (Dithering will remove hot pixels, please refer to The Dither Handbook at http://www.stsci.edu/instruments/wfpc2/Wfpc2_driz/wfpc2_driz.html for more information.)

A few major points about *crrej*:

- *crrej* works by taking the input images and creating an initial "guess image," by either taking the median or minimum of the values at each input pixel position (if there are only a few input images, *crrej.initial=min* is recommended).
- In the parameter *crrej.sigmas*, the user indicates the sigma rejection required for throwing out bad pixels. If more than one number is entered, separated by a comma, each value corresponds to a sigma rejection for a particular iteration. For instance, *crrej.sigmas=8,6,4* indicates that crrej will do three iterations of throwing out bad pixels. Pixel values outside an 8-sigma range of the initial image are thrown out in the first iteration, 6-sigma for the second iteration, and 4-sigma for the final iteration.
- If a pixel is affected by a cosmic ray, it will be thrown out as described in the paragraph above. But adjoining pixels to the one affected by a cosmic ray (the "bad" pixel) may contain elevated signals, and may have to be removed as well. There are two parameters for determining

this action. *radius* specifies how much of an area around the bad pixel should be checked. *pfactor* is the fractional value to apply to the sigmas (as specified in *crrej.sigmas*) to evaluate if those surrounding pixels should be rejected or not, during each iteration.

- An additional noise term to consider is provided by the parameter *scalenoise*, which accounts for the amount of fractional sub-pixel offsets that could be present between each input image. The default value in *crrej* has been optimized for WFPC2 data.
- The WFPC2 readnoise is 5 electrons, that's 0.71 DN for gain=7 and 0.3 DN for gain=15.
- The unrejected pixels in the input images are added to create the final image and normalized to the total image exposure time.

The values for *sigmas* and the number of its iterations, *scalenoise*, *radius*, and *pfactor* in the default settings for *crrej* are good starting points. These parameters generally depend on several factors such as exposure time, the number of images combined, and scientific goals. Users are advised to try different values and choose the parameter values best suited for their data. (Be sure to check that the peaks of stars in the final image are not being clipped.)

In the example below, two image sets will be combined:

F555W images u5ay0701r.c0h and u5ay0702r.c0h.
F814W images u5ay0704r.c0h and u5ay0705r.c0h.

We start with the default values in *crrej*. These defaults can be reset simply by typing:

```
unlearn crrej
```

Listed below are the *crrej* parameters with their default settings:

input = ""	Input images
output = ""	Output image name
masks = ""	Input/output masks (optional)
sigmas = "8,6,4"	Rejections levels in each iteration
(radius = 1.5)	CR expansion radius in pixels
(pfactor = 0.5)	CR expansion discriminator reduction factor
(initial = "min")	Initial value estimate scheme (min or med)
(lower = -99.)	Lower limit of usable data
(upper = 4096.)	Upper limit of usable data
(sky = "none")	How to compute the sky
(expname = "exptime")	Exposure time keyword name
(readnoise = "0.72")	Read noise(s) (in DN) of the detector(s)
(atodgain = "7")	Detector gain(s) in electrons/DN
(scalenoise = "3,1")	Multiplicative term (in PERCENT) from noise model
(dq = "")	Data quality filter pset
(skyname = "BACKGRND")	Name of the group parameter to be updated with the sky value

```
(crdqval = 128)         Data quality value for pixels flagged as cosmic ray
(fillval = 0.)          Fill value for pixels having no good values in all input images
(verbose = yes)         Print out verbose messages?
(mode = "al")
```

Before proceeding, check the A-to-D gain for the two images.

```
hedit u5ay0701r.c0h,u5ay0702r.c0h atodgain .
```

```
u5ay0701r.c0h,ATODGAIN = 7.0
u5ay0702r.c0h,ATODGAIN = 7.0
```

```
hedit u5ay0704r.c0h,u5ay0705r.c0h atodgain .
```

```
u5ay0704r.c0h,ATODGAIN = 7.0
u5ay0705r.c0h,ATODGAIN = 7.0
```

Also, make a back-up copy of the *.c1h and *.c1d files because *crrej* will change them to include data quality information about the cosmic rays in each input image.

Combine images u5ay0701r.c0h and u5ay0702r.c0h using *crrej*. But first, make a back-up copy of the data quality files. (The ! is used to execute a UNIX command within the IRAF environment.)

```
!mkdir data_qual_bkup
!cp *.c1h *.c1d data_qual_bkup/


crrej “u5ay0701r.c0h,u5ay0702r.c0h” f555w.hhh \
“u5ay0701r.c0h,u5ay0702r.c0h” “8,6,4” readnoise=0.71 atodgain=7
crrej “u5ay0704r.c0h,u5ay0705r.c0h” f814w.hhh \
“u5ay0704r.c1h,u5ay0705r.c1h” “8,6,4” readnoise=0.71 atodgain=7
```

2.4.11 *imedit* - Examine and edit pixels in images (*cl.images.tv*)

Editing images can be done using an interactive task called *imedit*. There is extensive on-line help available in IRAF. To get started, display the image using *saoimage* or *ximtool*, then fire up *imedit*.

```
imedit u5ay0701r.c0h[2] out_img.hhh
```

The first field specifies the input file, and the second field is the single-group output file.

To view a summary of *imedit* cursor commands, place the cursor on the image, then type **?**. Anytime you wish to undo a command, just type **u** to revert to the previous pixel values.

Listed below are some image editing suggestions. There are many more commands available, so please consult the on-line help file for more information:

- To remove a feature and substitute it with a local background value.
    - Place the cursor at the bottom left boundary of the feature area, then type **a**
    - Next, place the cursor at the top right of the feature, and type **a** again
    - (The order of clicks, top-left or bottom-right, is not important. The purpose is simply to define a box around the feature that will be edited.)
- To remove a feature but substitute it with a constant value.
    - Specify the value of the constant by placing the cursor on the image, then typing **:v <*value*>** where <*value*> is a numerical constant.
    - Then, use the cursor to mark the boundaries as outlined above, but hit **d** instead of **a**.
- Two cursor strokes mentioned in the examples above define rectangular areas to be edited. A circular aperture can also be specified.
    - First, set the radius size with the command **:radius** <*value*>, then position the cursor on the area to be edited.
    - For background value substitution, type **b** once.
    - For constant value substitution, type **e** (be sure to set the constant value before doing this).
- To exit the task and save the image editing results, place the cursor on the image and type **q.** If you don’t want to save the changes, type **Q**.

Note that the output file is a single-group image. If you wish to edit all four groups of a dataset, do the following: edit each group and save the results to a single-group image. Then combine them back into a 4-group image using the *imcopy* command. This technique is useful for IRAF tasks that only work with single images.

Run *imedit* on each group of the image u5ay0701r.c0h and save the results to four single-group images (img_?.hhh).

```
imedit u5ay0701r.c0h[1] img_1.hhh
imedit u5ay0701r.c0h[2] img_2.hhh
imedit u5ay0701r.c0h[3] img_3.hhh
imedit u5ay0701r.c0h[4] img_4.hhh
```

Then, combine the four single group images back into a single four-group image.

```
imcopy img_1.hhh img_all.c0h[1/4]
imcopy img_2.hhh img_all.c0h[2]
imcopy img_3.hhh img_all.c0h[3]
imcopy img_4.hhh img_all.c0h[4]
```

This way, the group header information is preserved, and other WFPC2 tasks like *wmosaic* can be run on the resulting 4-group dataset.

2.4.12 *wfixup* - Interpolate over bad columns in a WF/PC frame (*stsdas.hst_calib.wfpc*)

This task performs cosmetic touch-ups to images. *wfixup* accepts an input image and its associated data quality file (see section 2.5.2 for more information about data quality file flags). It identifies pixels flagged as "bad" in the data quality file, and performs a simple linear interpolation over those bad pixels.

In the example below, *wfixup* is performed on all four groups of a WFPC2 image, using its associated data quality file, and the results written to an output file called clean_img.hhh. In this example, the task parameters have been set such that the longest allowable length of continuous bad pixels to be interpolated is ten; if the width of consecutive bad pixels is greater than this, the pixel values are not changed.

```
wfixup u5ay0701r.c0h  u5ay0701r.c1h  clean_img.hhh  10  indef
```

2.4.13 *synphot* - Tasks for synthetic photometry and modelling instrument response. (*stsdas.hst_calib*)

synphot is a software package that simulates photometric data and spectra for HST instruments. It is useful for such things as predicting count rates in any observing mode, plotting HST calibration target spectra, plotting sensitivity curves for various observing modes, as well as examining the photometric transformations between HST observing modes and conventional systems such as Johnson-Cousins UBVRI.

Full details about the many different features of *synphot* are best obtained from the Synphot Users Manual, available on-line at http://stsdas.stsci.edu/Document3.html

More information about each *synphot* task can also be found in the on-line STSDAS help files. Other WFPC2-related Synphot information can be found at: http://www.stsci.edu/instruments/wfpc2/wfpc2_doc.html#Phot

Atlases of HST standard star spectra, as well as observed and synthetic spectra from other atlases (such as the Bruzual-Persson-Gunn-Stryker Atlas), can be downloaded from the institute web site at http://www.stsci.edu/ftp/instrument_news/Observatory/cdbs/astronomical_catalogs_alt.html

The following are examples illustrating the use of three commonly-used *synphot* tasks.

- *plband* - Plots a synthetic passband using the individual throughputs of the telescope components (such as instrument, filters, and gain), an optional wavelength table supplied by the user, and a functional form of the passband to be plotted (Gaussian or a rectangular window).
- *calcphot* - calculates predicted count rates or fluxes in a given passband for a specified object. Also provides other information such as average wavelength, full-width- at-half-maximum, and rms wavelength.
- *plspec* -Plots synthetic spectra generated from observation mode and spectrum expressions.

Example 1:

Plot the F555W bandpass, normalized to a maximum value of 1 with wavelength range between 4000 Å to 8000 Å. Then, overplot the Johnson V bandpass (using dotted lines) for comparison.

```
plband wfpc2,f555w left=4000 right=8000 norm+
plband v ltype=dashed left=3000 right=9000 app+
```

The *app+* parameter in the second *plband* command specifies that the second plot to be overplotted over the first one.

Save the plot to a postscript file: at the *cl* prompt, enter the *cursors* mode by typing

```
=gcur
```

To snap a "photo" of the plot and save it to a postscript file, type

```
:.snap psi_defm
```

(The *psi_defm* option creates a black and white graph.)

Type

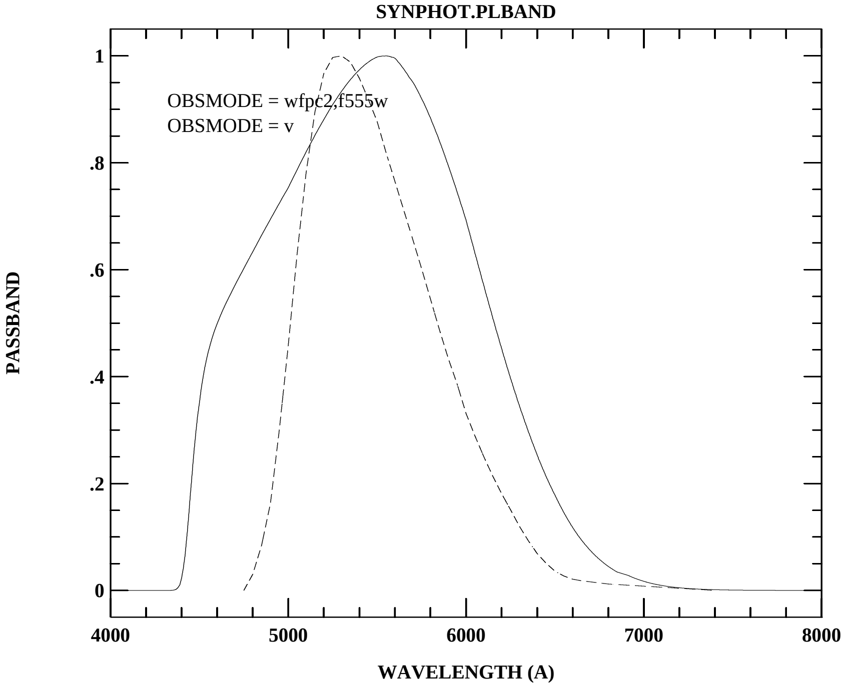
***q* or <*return*>**

to return to the IRAF command mode.

The *snap* command in *cursors* creates a postscript file with a randomly selected name in the /tmp directory. It can be copied and renamed to the working directory.

```
mv /tmp/psk8623a f555w_v.ps
```

Figure 2: Plot from Example 1, showing the bandpasses for F555W (soild) and Johnson V(dashed).



Example 2:

Calculate the predicted countrate for one of HST's standard stars, GRW+70d5824, in the WFPC2 using the PC chip, gain 7, and F814W.

First, retrieve the table (in FITS format) containing the spectrum for GRW+70d5824 from the location mentioned at the beginning of this section.

Then, type

```
calcphot wfpc2,1,a2d7,f814w grw_70d5824_012.fits counts
Mode = band(wfpc2,1,a2d7,f814w)
   Pivot       Equiv Gaussian
 Wavelength         FWHM
  7995.943       1521.478    band(wfpc2,1,a2d7,f814w)
Spectrum:  grw_70d5824_012.fits
    VZERO      (COUNTS s^-1 hstarea^-1)
       0.            2896.707
```

Example 3:

In this example, we plot some results from *calcphot*. We will determine the integrated counts in four WFPC2 filters, F439W, F555W, F675W, and F814W in the PC at gain 7, for star #111 in the Bruzual-Persson-Gunn-Stryker Atlas (bpgs_111) that's normalized to a V magnitude of 16.

First, retrieve the table containing the spectra of star bpgs111.

Then, type

```
calcphot @modes.lis "rn(bpgs_111.fits,band(v),16.0,vegamag)" \
counts out=bpgs111_results
```

where *modes.list* is a file containing a list of WFPC2 modes

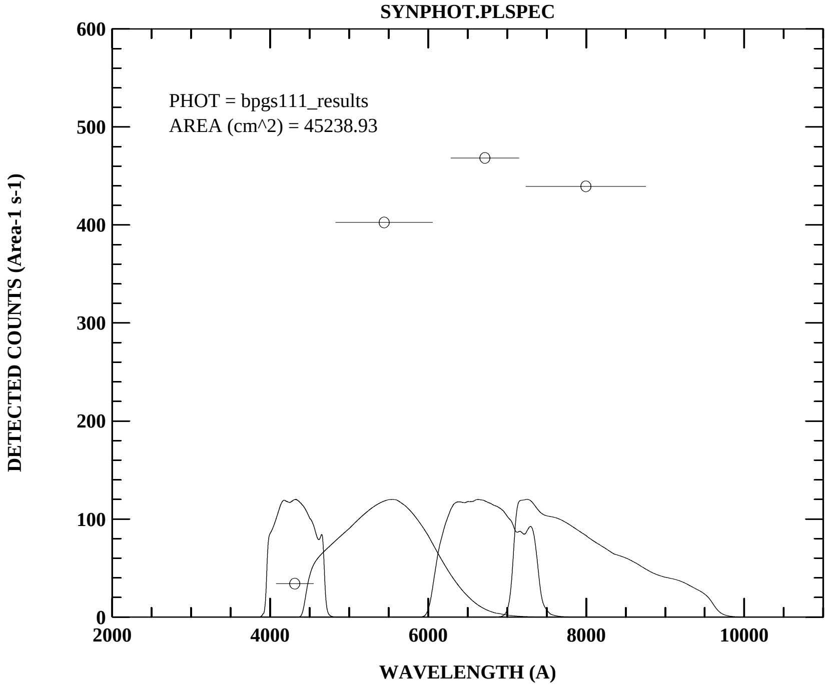
```
wfpc2,1,f439w,a2d7
wfpc2,1,f555w,a2d7
wfpc2,1,f675w,a2d7
wfpc2,1,f814w,a2d7
```

```
 Mode = band(wfpc2,1,f439w,a2d7)
   Pivot       Equiv Gaussian
 Wavelength         FWHM
  4312.094       476.4165    band(wfpc2,1,f439w,a2d7)
Spectrum:  rn(bpgs_111.fits,band(v),16.0,vegamag)
    VZERO      (COUNTS s^-1 hstarea^-1)
       0.           34.04943

Mode = band(wfpc2,1,f555w,a2d7)
   Pivot       Equiv Gaussian
 Wavelength         FWHM
  5442.932       1229.781    band(wfpc2,1,f555w,a2d7)
Spectrum:  rn(bpgs_111.fits,band(v),16.0,vegamag)
    VZERO      (COUNTS s^-1 hstarea^-1)
       0.           402.5876

Mode = band(wfpc2,1,f675w,a2d7)
   Pivot       Equiv Gaussian
 Wavelength         FWHM
  6717.713       867.2123    band(wfpc2,1,f675w,a2d7)
Spectrum:  rn(bpgs_111.fits,band(v),16.0,vegamag)
    VZERO      (COUNTS s^-1 hstarea^-1)
       0.           468.4425

Mode = band(wfpc2,1,f814w,a2d7)
   Pivot       Equiv Gaussian
 Wavelength         FWHM
  7995.939       1521.494    band(wfpc2,1,f814w,a2d7)
Spectrum:  rn(bpgs_111.fits,band(v),16.0,vegamag)
    VZERO      (COUNTS s^-1 hstarea^-1)
       0.           439.4594
```

To plot the results

```
plspec "" "" counts pfile=bpgs111_results left=2000 right=11000 \
bottom=0 top=600
```

Figure 3: Plot from Example 3. The bandpass for F439W, F555W, F675W, and F814W are shown. The four symbols (circle with line through it) are countrates for star bpgs111 for v=16 in the four respective filters where gain=7 and chip=PC.



2.5 Assessing Data Quality: Bias Jumps, Image Defects, Jitter

Before proceeding with data analysis, it’s always a good idea to check the quality of the WFPC2 images.

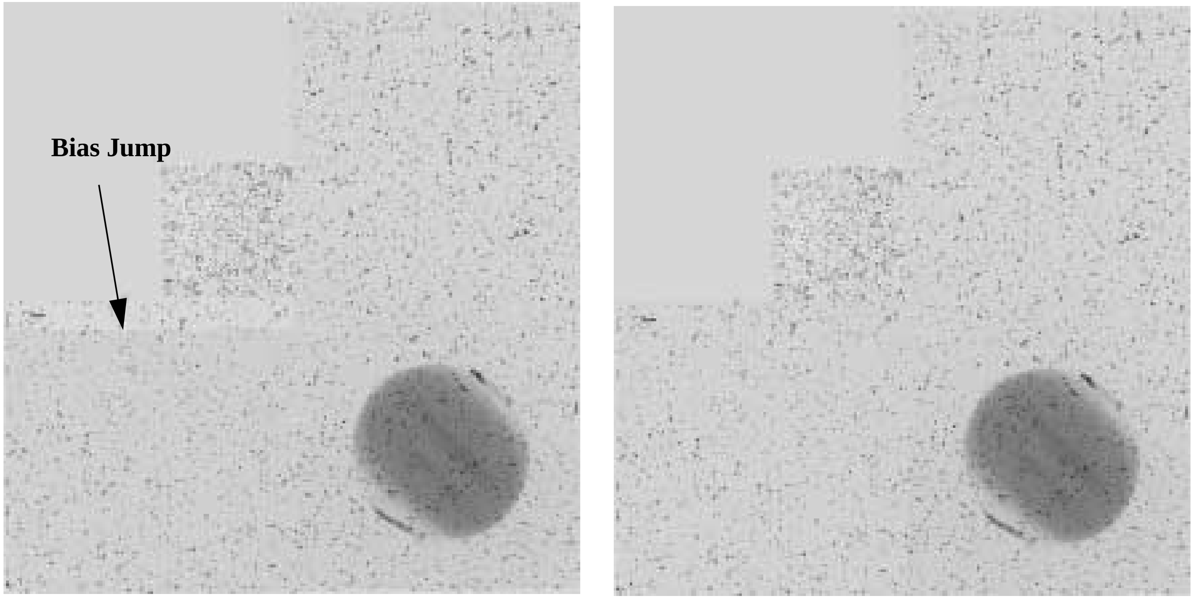
2.5.1 Bias Jumps

Bias jumps, which appear as diffuse background bands in some WFPC2 images, are believed to be due to changes in the CCD bias level during chip readout. These jumps also appear in the chip overscan image (.x0h file). The cause of bias jumps is not completely understood, but are thought to be associated with other spacecraft activities.

The WFPC2 pipeline calibration software, *calwp2*, detects the occurrences of bias jumps and records it in the calibrated data header file (.c0h). A record of bias jumps for each chip can be viewed by simply paging the header file (using the UNIX commands *page* or *more*, or the IRAF command *imheader*.) In most cases, the jumps are very small, just a few tenths of a DN and may not even be visible in the image. If a jump is 0.5 DN or larger, it’s recorded in the calibrated header file as a "Warning".

Depending on your science goals, it may or may not be necessary to correct a bias jump. The following steps outline a procedure for correcting an image affected by a bias jump in one chip. In this example, we use an image (*u3b10602t*) with a bias jump of 0.589 DN in the WF2. One of the files required for the correction is the images's flat field reference file, and for this image, it is f4i1559cu.r4h. Also, if the exposure time is less than 10 seconds, the shutter shading reference file is needed.

Figure 4: A mosaic of image u3b10602t.c0h (Jupiter taken with filter F160BN15). The left image shows the bias jump in WF2. On the right, the image has been corrected.



1. From the image display, determine the approximate position of the bias jump in WF2. The bias jump band is seen from y=1 to y=112 in chip 2's coordinate system.

2. Run *imstat* on the x0h file to get the precise location of the jump. Check only columns 5:14 (this is the "good" region in the overscan area that is used for the determining bias level). The following *imstat* commands were run in the region where the bias jump was seen to occur. The results will help us fine-tune the location where the jump occurs. Create a file named *list* containing the following image section names

```
u3b10602t.x0h[2][5:14,110]
u3b10602t.x0h[2][5:14,111]
u3b10602t.x0h[2][5:14,112]
u3b10602t.x0h[2][5:14,113]
u3b10602t.x0h[2][5:14,114]
```

Run *imstat* on the images listed in the file *list*

```
imstat @list
```

```
IMAGE                        NPIX    MEAN     STDDEV    MIN     MAX
u3b10602t.x0h[2][5:14,110]   10      352.7    0.6749    352.    354.
u3b10602t.x0h[2][5:14,111]   10      352.2    0.6325    351.    353.
u3b10602t.x0h[2][5:14,112]   10      352.8    0.7888    352.    354.
u3b10602t.x0h[2][5:14,113]   10      353.4    0.6992    352.    354.
u3b10602t.x0h[2][5:14,114]   10      353.6    0.6992    353.    355.
```

The statistics above indicate that the bias jump occurred at y=113.

3. For areas above and below the jump, get the mean value of the pixels.

```
imstat u3b10602t.x0h[2][5:14,1:112]
```

```
# IMAGE                          NPIX    MEAN    STDDEV   MIN    MAX    MIDPT
u3b10602t.x0h[2][5:14,1:112]     1120    352.7   0.7028   351.   355.   353.
```

```
imstat u3b10602t.x0h[2][5:14,113:800]
```

```
# IMAGE                          NPIX    MEAN    STDDEV   MIN    MAX    MIDPT
u3b10602t.x0h[2][5:14,113:800]   6880    353.3   0.7302   351.   356.   353.
```

Also get the mean value of all pixels in the overscan area u3b10602t.x0h[2][5:14,1:800].

```
imstat u3b10602t.x0h[2][5:14,1:800]
```

```
# IMAGE                          NPIX    MEAN    STDDEV    MIN    MAX    MIDPT
u3b10602t.x0h[2][5:14,1:800]     8000    353.2   0.7523    351.   356.   353.
```

In the area before the jump, mean bias value = 352.7 DN

In the area after the jump, mean bias value = 353.3 DN

The mean bias value = 353.2 DN

The difference in bias for the two regions affected by the jump in the image u3b10602t.c0h[2]:

Line 1 to 112: 352.7 - 353.2 = -0.5 DN

Line 112 to 800: 353.3 - 353.2 = 0.1 DN

4. Create a one-group correction image that will be applied to the WF2 image affected by the jump:

   - Create a bias "difference" image

     ```
     imcalc u3b10602t.c0h[2] correct1.hhh  "if y .lt. 113 then (0.5) else (-0.1)"
     ```

   - Apply this correction to the image's flat field reference file, f4i1559cu.r4h. This is done because the flat-field file, which is normalized to 1, is multiplied with the image during the calibration process. Therefore, the same adjustment needs to be made to the bias level corrections that will be applied as well.

     ```
     imcalc "correct1.hhh,f4i1559cu.r4h[2]" correct2 "im1 * im2"
     ```

   - If the exposure time is less than 10s, a correction needs to be made using the shutter shading reference file. Since the exposure time for this image was 500 seconds, this correction is unnecessary. But for the sake of illustrating how the correction is done, assume that the exposure time for this image is 6 seconds. Its shutter shading reference file is e371355eu.r5h. The correction would look like this:

     ```
     imcalc "correct2,e371355eu.r5h[2]" correct3.hhh "im1 * (1 + im2/6)"
     ```

   - Create the corrected image

     ```
     imcopy u3b10602t.c0h[1] corrected_img.hhh[1/4]
     imcalc "u3b10602t.c0h[2],correct2" corrected_img.hhh[2] "im1+im2"
     imcopy u3b10602t.c0h[3] corrected_img.hhh[3]
     imcopy u3b10602t.c0h[4] corrected_img.hhh[4]
     ```

     (Note: if the exposure time was less than 10 seconds, multiply the WF2 image by the modified shutter shading reference file (correct3.hhh).

2.5.2 Data Quality Files

- For each observation, a set of ascii data quality files are created, with the extensions .pdq and .trl. The .trl file, generated during pipeline calibration, contains a log of calibration steps. The .pdq file contains information about the actual and predicted observational parameters, and any obvious features that may have been noted by the post-observation processing staff. You should page through these files to look for anything that would indicate a problem with the data.
- The calibrated science image (extensions .c0h and .c0d) has an associated data quality file (.c1h and .c1d) that provides information about the quality of each pixel in a science image. Bad pixels in the science image are flagged in the data quality image; these flagged pixels are designated non-zero positive values indicating the nature of the pixel problem (listed below). The values in the pixels are additive; a value of 3 would indicate a combination of 1 and 2.

Value	Description
0	Good pixels.
1	Reed-Solomon decoding error. Pixels in a data packet that were corrupted during data transmission.
2	Defect in one of the calibration reference files used in calibration or recalibration. Includes charge transfer traps.
8	A-to-D converter saturation. Signal that is greater than or equal to the maximum A-to-D value (4096).
16	Pixel value was lost during readout or data transmission.
256	Pixels lying above a charge transfer trap that may be affected by the trap.
512	Unrepairable hot pixel.
1024	Repairable hot pixel.

How do I determine if any bad pixels fall on critical parts of my science image? Blink the science and data quality images. First, display the science image, then display the data quality file, and “blink” them.

Hint: When displaying the data quality image (.c1h, .c1d), first run *wstatistics* on the file to determine the minimum and maximum values. Set the lower and upper display ranges (*z1* and *z2* parameters) to match those minimum/maximum values (and be sure to set *zrange* and *zscale* to “no”). This will produce an image display of the data quality file clearly showing the bad pixels. A bad pixel’s value can then be determined by placing the image display cursor on it. Remember that these displayed values are not exact, but are close enough for you to determine what the pixel value should be. (For an exact value of a particular pixel, use the task *listpix*.)

2.5.3 Using Jitter Files to Evaluate Pointing.

The jitter files (also known as Observation Log files) contain information about telescope pointing during an observation, as well as related engineering data. You might be interested in checking these files if you are concerned about the quality of the point spread feature in your stellar image (the FWHM for stars can be measured using *imexam*.) More details about these files can be found in the HST Data Handbook Appendix (http://www.stsci.edu/hst/HST_overview/documents/datahandbook/) and the STScI Observatory Support observation log documentation page at http://www.stsci.edu/instruments/observatory/obslog/OL_1.html

Due to improvements to the jitter files over the history of the telescope, there are different types of file formats available, depending on when the observations were taken. In this document, we only deal with FITS jitter files that were generated after 1997. Information about pre-1997 jitter files can be obtained from the above-mentioned documentation.

Jitter files have the same rootname as the images they are associated with, except that the rootname ends with a j. The information in these files spans not only the exposure time, but also the pre- and post-observation overheads starting from the time guide stars were acquired. (Note: the jitter files used in this example are in the extension FITS format, and cannot be converted to GEIS files.)

There are two types of jitter files, ".jif" and ".jit".

1. Jitter files with the". jif" extension contains general pointing information for the observation.

    - The header component of this FITS file contains keywords for guide stars used, pointing and spacecraft jitter, as well as pointing anomalies, if any. Also included is general information about other observing parameters such as modelled background light and orbital geometry.

      Some useful keywords to check in the .jif file

GUIDECMD	Commanded Guiding Mode
TNLOSSES	Number of loss of lock events
TLOCKLOS	Total loss of lock time
TNRECENT	Number of recentering events
TRECENTR	Total recentering time
TV2_RMS	RMS jitter along V2 axis
TV3_RMS	RMS jitter along V3 axis
T_ACQ2FL	Target acquisition failures
T_GSFAIL	Guide star acquisition failures
T_SGSTAR	Failure of single star fine lock
T_TAPDRP	Possible loss of science data

      Some keywords will only show up if there’s a problem with the observation. They include:

GSFAIL	The telescope failed to acquire the guide stars.
TAPEDROP	Potential loss of science data
TLM_PROB	A problem with the engineering telemetry
SLEWING	Slewing occurred during the observation
TAKEDATA	Take Data Flag NOT on throughout observation
SI_PROBnn	(where n=1-99) Miscellaneous instrument problems.

      A more complete description of these header keywords can be found at http://www.stsci.edu/instruments/observatory/obslog/OL_8.html

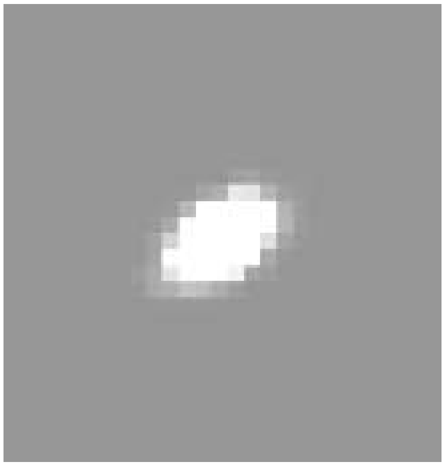
Check the guiding mode, number of loss of lock events, and RMS jitter in milliarcseconds along the V2 and V3 axis for all jitter files in the directory.

```
hsel *jif.fits[0] $I,GUIDECMD,TNLOSSES,TV2_RMS,TV3_RMS yes
```

```
u5ay0701j_jif.fits[0]    "FINE LOCK"   0   2.6   3.9
u5ay0702j_jif.fits[0]    "FINE LOCK"   0   2.6   4.2
u5ay0703j_jif.fits[0]    "FINE LOCK"   0   3.0   3.7
u5ay0704j_jif.fits[0]    "FINE LOCK"   0   2.7   4.1
u5ay0705j_jif.fits[0]    "FINE LOCK"   0   2.6   4.2
u5ay0706j_jif.fits[0]    "FINE LOCK"   0   2.8   4.3
u5ay0707j_jif.fits[0]    "FINE LOCK"   0   2.8   4.3
u5ay0708j_jif.fits[0]    "FINE LOCK"   0   2.7   4.2
u5ay0709j_jif.fits[0]    "FINE LOCK"   0   2.6   4.1
u5ay070aj_jif.fits[0]    "FINE LOCK"   0   2.6   4.2
```

The image portion of the jif file, seen here in Figure 5, shows a 64x64 pixel image of the pointing excursion from the center, where the pixel scale is 2 milliarseconds. This 2-dimensional histogram indicates that there is slightly more jitter along one axis than the other (which is normal for most observations).

Figure 5: The image portion of the *jif.fits file showing an image of the pointing excursion from the center.



2. The other kind of jitter file has the extension ".jit". It’s a table containing various values including jitter along V2 and V3, where each jitter value is an average over a 3 second interval. To get a sense of the jitter during the observing window, the 3-second-averaged jitter in either the V2 axis or V3 axis can be plotted:

```
sgraph "u5ay0701j_jit.fits seconds si_v2_avg"        # See Figure 6
```

To look at pointing stability during the observing window, plot the jitter in V2 versus jitter in V3.

```
sgraph "u5ay0701j_jit.fits si_v2_avg si_v3_avg"      # See Figure 7
```

Figure 6: Plot of 3-second-averaged jitter in the V2 axis versus time that the telescope was pointing at the target for a particular observation (time axis includes pre- and post-observation setup times)

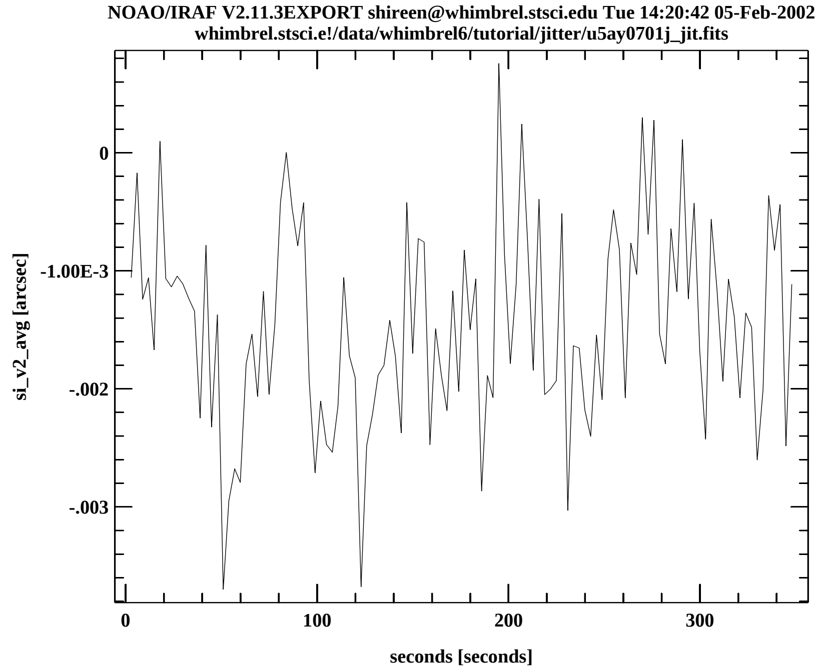
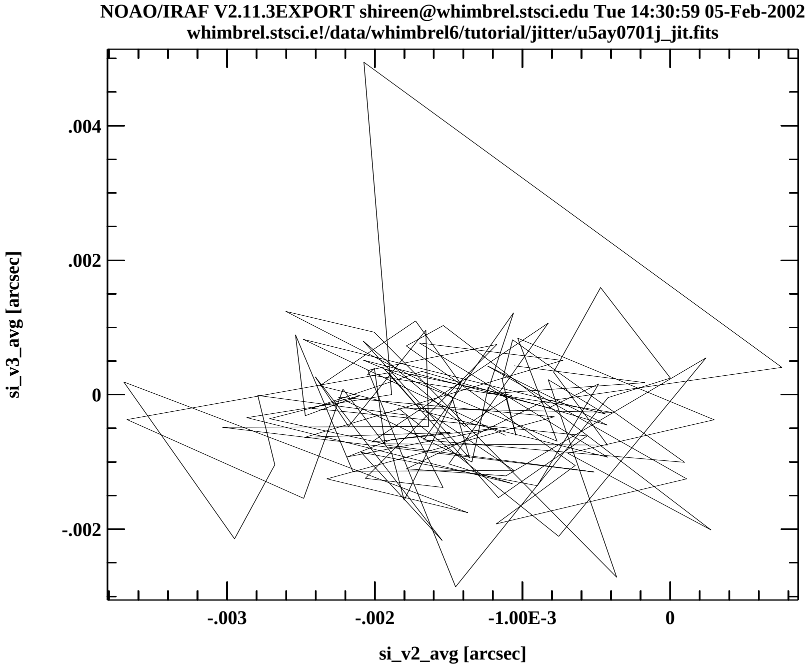


Figure 7: Plot of jitter in V2 vs. jitter in V3, showing the pointing stability during the observing window.



Evaluating pointing accuracy for your observations

There are three different types of guiding scenarios:

1. Two FGS Fine Lock Guiding. This mode uses two guide stars, one in each of two Fine Guidance Sensors, to lock on a target. Of the three guiding modes, this produces the most accurate pointing. During an observation, the pointing can vary by about 1 to 50 milliarcseconds, depending on various spacecraft and observing parameters.
2. Gyro Control. The Rate Gyro Assembly controls pitch, yaw and roll of the telescope. Of the three guiding modes, this has the least accurate pointing, producing drifts on the order of 1 to 5 milliarcseconds per second.
3. Single FGS plus gyro: one guide star is used but the telescope roll is controlled by gyros. Errors are about 1 to 5 milliarcseconds per second of roll about the dominant guide star.

For more information about pointing accuracy and jitter files, please go to

http://www.stsci.edu/instruments/observatory/obslog/OL_7.html#HEADING55

3. Calibration and Recalibration

Data arrives at STScI in the form of original telemetry files (known as "POD" files). Each POD file is partitioned into science and engineering files. It then undergoes various processing steps such as data editing and generic conversion, resulting in raw data files (.d0h/.d0d, .q0h/.q0d, etc.). Raw image data is then calibrated with the WFPC2 calibration pipeline software, *calwp2*, using the best-available calibration reference files. However, these raw and calibrated data files are no longer archived. After certain keyword values and image information are collected for storage in a database, the raw and calibrated files are deleted. Later, when a user requests a particular dataset, the On-the-fly Reprocessing system (OTFR) grabs the dataset's POD file from the archive, processes it to create raw data which are calibrated with the best-available reference files using *calwp2*. The raw and calibrated data are then sent to the user.

This section presents an overview of calibration steps for WFPC2 data. Thanks to the OTFR system, all data requested by users are processed with the latest software, and the best-available calibration reference files, at the time of the request. Therefore, there's little reason for users to manually recalibrate their data unless they need to use non-default calibration reference files.

Calibrated data retrieved from the archive within about 2 weeks of an observation will probably use older dark calibration files. That's because dark calibration files for the time of the observations have not yet been created -- they are typically available about 2 weeks after the date of the observation. If you wish to use the best possible dark reference files, you should check StarView to see if the appropriate dark calibration files for your observations are ready, and when it is, re-request the data again so that it can be calibrated with the best dark calibration files.

3.1 Input and Output Files in the Calibration Process

(The file extensions are noted in parenthesis.)

The input data files are:

- Raw data (.d0h, .d0d).
- Data quality files for raw science data (.q0h, .q0d).
- Standard header packet containing observation parameters (.shh, .shd) [Although a part of the raw data set, it is not used by *calwp2*].

Note: The extracted engineering files (.x0h, .x0d), and its associated data quality files (.q1h, .q1d) are part of the raw dataset. But they are used during calibration and are therefore listed in the next category.

The input calibration reference files are:

- Static mask file (.r0h, .r0d).
- A-to-D (analog-to-digital converter) correction file (.r1h, .r1d).
- Extracted engineering data (.x0h, .x0d), and its data quality file (.q1h, .q1d). [This is the chip overscan area. It's a component of the raw dataset retrieved from the archive.]
- Bias image reference file (.r2h, .r2d), and its data quality file (.b2h, .b2d).
- Dark image reference file (.r3h, .r3d), and its data quality file (.b3h, .b3d). [Only used for exposures over 10s.]
- Flat field file (.r4h, .r4d), and its data quality file (.b4h, .b4d).
- Shutter shading correction (.r5h, .r5d). [Only used for exposures under 10s.]
- HST Graphs Table (.tmg) and Components Table (.tmc), throughput tables used to determine photometric information for a dataset.

After running *calwp2*, output files are:

- Calibrated science data (.c0h, .c0d).
- Data quality files for calibrated science data (.c1h, .c1d).
- Histogram of good science data pixel values (.c2h, .c2d) [optional].
- Photometric throughput table for the dataset (.c3t).
- ASCII file containing group parameters and their values (.cgr).

Data obtained from the archive also include:

- File containing group parameters in ASCII format. It's only used in the pipeline and is not needed if you recalibrate your data. (.dgr)
- The Standard Header Packet, not used by *calwp2* but it's part of the standard WFPC2 dataset. (.shh, .shd)

3.2 The Calibration Steps

Each individual calibration step can be executed by setting a "switch" in the raw data header file. This way, if a particular calibration step is unnecessary, it does not have to be performed when you recalibrate the data using *calwp2*.

What are the calibration steps?

Each calibration step is listed below in the order it is done:

1. The **static mask reference file (.r0h, .r0d)** identifies charge transfer traps and other pixels affected by the traps. This information is entered in the calibrated image data quality file (.c1h, .c1d). The image data (.c0h, .c0d) itself is not changed.

   The header keyword switch is ***MASKCORR***.
   The header keyword indicating the calibration filename is ***MASKFILE***.

2. The **A-to-D reference file (.r1h, .r1d)** corrects each pixel value of the science data for analog-to-digital conversion errors.

   The header keyword switch is ***ATODCORR.***
   The header keyword indicating the calibration filename is ***ATODFILE***.

3. A mean bias level is subtracted from each pixel in the science image. This value, one for each chip, is derived from a subset of the overscan region for that chip. The overscan regions are stored in the **extracted engineering file (.x0h, .x0d)**. (Its **data quality file (.q1h, .q1d)** contains bad pixel information that is also flagged in the calibrated science data quality file (.c1h, .c1d).)

   The header keyword switch is ***BLEVCORR***.

The header keyword indicating the calibration filename is ***BLEVFILE***.

The header keyword indicating the calibration data quality filename is ***BLEVDFIL***.

4. Position-dependent bias patterns are subtracted from the science data using the **bias pattern reference file**, also referred to as the **superbias file (.r2h, .r2d)**. Bad pixels in the bias pattern reference file are recorded in its **data quality file (.b2h, .b2d)**, and are also flagged in the science data quality file (.c1h, .c1d) during calibration.

   The header keyword switch is ***BIASCORR***.

   The header keyword indicating the calibration filename is ***BIASFILE***.

   The header keyword indicating the calibration data quality filename is ***BIASDFIL***.

5. The **dark reference file (.r3h, .r3d)**, and its **data quality file (.b3h, .b3d)**, are generated about every week. Dark reference files are only needed for observations where the header keyword DARKTIME is greater than 10s.

   The header keyword switch is ***DARKCORR***.

   The header keyword indicating the calibration filename is ***DARKFILE***.

   The header keyword indicating the calibration data quality filename is ***DARKDFIL***.

6. The science image is multiplied with a **flat field reference image (.r4h, .r4d)**. Information about bad pixels in the flat field reference image is found in its **data quality file (.b4h, .b4d)**, and flagged in the science image data quality file (.c1h, .c1d) during calibration.

   The header keyword switch is ***FLATCORR***.

   The header keyword indicating the calibration filename is ***FLATFILE***.

   The header keyword indicating the calibration data quality filename is ***FLATDFIL***.

7. For exposures less than 10 seconds, a **shutter shading correction file (.r5h, .r5d)** must be applied to the science data. This is necessary because the finite shutter velocity creates a “shading” effect in the image. This shading effect also depends on which of the two shutters is used (either shutter A or B).

   The header keyword switch is ***SHADCORR***.

   The header keyword indicating the calibration filename is ***SHADFILE***.

8. In order to populate photometry-related keywords in the calibrated science header files, set the keyword switch ***DOPHOTOM*** in the “.d0h” file to ***PERFORM***. During calibration, values for the following keywords will be calculated using *Synphot*:

PHOTMODE
PHOTFLAM
PHOTPLAM
PHOTBW
PHOTZPT

This step uses two tables, a **graph table (.tmg)** and a **component table (.tmc)** containing telescope and instrument throughput information. These tables are often updated for all on-board HST instruments as new results from ongoing calibration activities become available. To find out the names of the latest WFPC2 throughput tables, see the WFPC2 Synphot memo at

http://www.stsci.edu/ftp/instrument_news/WFPC2/Wfpc2_phot/wfpc2_synphot.html#summary

For example, as of February 6, 2002, the latest WFPC2 throughput tables were

m1p1255om_tmg.fits
m1s1421hm_tmc.fits

This calibration step will not change the pixel data values, it will only populate the header photometry keywords. This is useful for people who plan to use a flux-based photometric system such as the AB or STMAG system. More information about different photometric systems can be found in section 4 and the WFPC2 Data Handbook.

In addition, a **throughput table (.c3t)** will be created by *calwp2* using the *synphot* program.

The header keyword switch is ***DOPHOTOM***.
The header keywords indicating the calibration tables are ***GRAPHTAB*** for the graph table **(.tmg)**, and ***COMPTAB*** for the components table **(.tmc)**.

9. An optional calibration step is to generate a file containing histograms of raw data, A-to-D corrected data, and the final calibrated output data for each group. This file **(.c2h, .c2d)** will contain histograms of raw data in row 1, A-to-D corrected data in row 2, and the final calibrated data in row 3.

   The header keyword switch is ***DOHISTOS***.

10. The image datatype is specified in the input image header file.

    The header keyword is ***OUTDTYPE***, and can be set to either REAL, LONG or SHORT.

Note: During the calibration process, *calwp2* detects saturated pixels in the raw image file (.d0h, .d0d), and flags them in the calibrated data quality file

(.c1h, .c1d). Therefore, the keyword switch *DOSATMAP*, which creates an image map of saturated pixels is unnecessary, and may be set to OMIT.

More information on the calibration steps can be obtained from the WFPC2 section in the HST Data Handbook for WFPC2, version 4.0, located at http://www.stsci.edu/instruments/wfpc2/Wfpc2_dhb/WFPC2_longdhbcover.html

3.3 The Calibration Procedure

Recalibrating the dataset u5ay0701r

StarView, can be used to determine which reference files should be used for recalibration; at the *Searches* menu item go to *STScI --> Instruments --> WFPC2 --> WFPC2 Reference Files*. Enter the dataset in the table-like section at the top of the search window. Or you can search for the reference file you want to use at *Searches --> STScI --> Instruments --> WFPC2 --> WFPC2 Calibration Data*.

Example: Calibration reference files needed for u5ay0701r:

Type of Calibration	Calibration Header Filename	Switch (recommended)
A-to-D Correction:	DBU1405IU.R1H	perform
Bias Correction:	KCD1557LU.R2H	perform
Dark Current Correction:	JAE1431QU.R3H	perform
Flat Field Correction:	G640925NU.R4H	perform
Static Pixel Mask:	F8213081U.R0H	perform
Shutter Shading File:	E371355IU.R5H	omit
Engineering File:	U5AY0701R.X0H	perform
Photometric Calibration Table:	U5AY0701R.C3T	perform
Graph Table:	M1P1255OM_TMG.FITS	
Components Table:	M1S1421HM_TMC.FITS	

Each calibration step will be executed in *calwp2* if the input image header keyword “switch” is set to PERFORM. The step will not be executed if the “switch” is set to OMIT. The next listing shows an excerpt of a raw data header file (.d0h) with the calibration keyword switches.

```
                          / RSDP CONTROL KEYWORDS
MASKCORR=     'PERFORM '  / Do mask correction: PERFORM, OMIT, COMPLETE
ATODCORR=     'PERFORM '  / Do A-to-D correction: PERFORM, OMIT, COMPLETE
BLEVCORR=     'PERFORM '  / Do bias level correction
BIASCORR=     'PERFORM '  / Do bias correction: PERFORM, OMIT, COMPLETE
DARKCORR=     'PERFORM '  / Do dark correction: PERFORM, OMIT, COMPLETE
FLATCORR=     'PERFORM '  / Do flat field correction
SHADCORR=     'OMIT    '  / Do shaded shutter correction
DOSATMAP=     'OMIT    '  / Output saturated pixel map
DOPHOTOM=     'PERFORM '  / Fill photometry keywords
DOHISTOS=     'OMIT    '  / Make histograms: PERFORM, OMIT, COMPLETE
OUTDTYPE=     'REAL  '    / Output image datatype: REAL, LONG, SHORT
```

The following is an excerpt from the raw data header file, u5ay0701r.d0h, listing the calibration reference files (*uref*, *ucal*, and *mtab* are IRAF pointers to files -- more on this later):

```
                          /CALIBRATION REFERENCE FILES
MASKFILE=     'uref$f8213081u.r0h    '    / name of the input DQF of known bad pixels
ATODFILE=     'uref$dbu1405iu.r1h    '    / name of the A-to-D conversion file
BLEVFILE=     'ucal$u5ay0701r.x0h    '    / Engineering file with extended register da
BLEVDFIL=     'ucal$u5ay0701r.q1h    '    / Engineering file DQF
BIASFILE=     'uref$kcd1557lu.r2h    '    / name of the bias frame reference file
BIASDFIL=     'uref$kcd1557lu.b2h    '    / name of the bias frame reference DQF
DARKFILE=     'uref$jae1431qu.r3h    '    / name of the dark reference file
DARKDFIL=     'uref$jae1431qu.b3h    '    / name of the dark reference DQF
FLATFILE=     'uref$g640925nu.r4h    '    / name of the flat field reference file
FLATDFIL=     'uref$g640925nu.b4h    '    / name of the flat field reference DQF
SHADFILE=     'uref$e371355iu.r5h    '    / name of the reference file for shutter sha
PHOTTAB =     '                      '    / name of the photometry calibration table
GRAPHTAB=     'mtab$k4j0855mm_tmg.fits'   / the HST graph table
COMPTAB =     'mtab$m1a15296m_tmc.fits'   / the HST components table
```

How do I set the new reference files and switches for recalibration?

Before running *calwp2*, the appropriate calibration files and calibration "switches" have to be set in the raw image header file (.d0h,). One way to do this is using the task *chcalpar* (found in the package *stsdas.hst_calib.ctools*).

chcalpar (CHange CALibration PARameters) is an easy way to edit GEIS header files. It is actually a task that calls other related tasks called "psets". When *chcalpar* is executed, it looks at the data to determine which instrument was used. Since our datasets are WFPC2 images, *chcalpar* will call the pset *ckwwfp2* to edit the raw image header file.

Example

chcalpar u5ay0701r.d0h

This command will call the WFPC2 pset *ckwwfp2* which will list all the default header keyword switches and reference files for u5ay0701r.d0h:

```
PACKAGE = ctools
  TASK = ckwwfp2
(maskcor=       perform)              >do mask correction?
(atodcor=       perform)              >Do A-to-D correction?
(blevcor=       perform)              >do bias level correction?
(biascor=       perform)              >do bias correction?
(darkcor=       perform)              >do dark correction?
(flatcor=       perform)              >do flat field correction?
(shadcor=       omit)                 >Do shaded shutter correction?
(dophoto=       perform)              >fill photometry keywords?
(dohisto=       omit)                 >Make histograms?
(outdtyp=       real)                 >output image data type?
(maskfil=       uref$f8213081u.r0h)   >name of the input DQF of known bad pixels
(atodfil=       uref$dbu1405iu.r1h)   >name of the A-to-D conversion
(blevfil=       ucal$u5ay0701r.x0h)   >engineering file with extended register data
(blevdfi=       ucal$u5ay0701r.q1h)   >engineering file DQF
(biasfil=       uref$kcd1557lu.r2h)   >name of the bias frame reference file
(biasdfi=       uref$kcd1557lu.b2h)   >name of the bias frame reference DQF
(darkfil=       uref$jae1431qu.r3h)   >name of the dark reference file
(darkdfi=       uref$jae1431qu.b3h)   >name of the dark reference DQF
(flatfil=       uref$g640925nu.r4h)   >name of the flat field reference file
(flatdfi=       uref$g640925nu.b4h)   >name of the flat field reference DQF
(shadfil=       uref$e371355iu.r5h)   >name of the reference file for shaded shutter c
(phottab=        )                    >name of the photometry calibration table
(graphta=       mtab$k4j0855mm_tmg.fits)>the HST graph table
(comptab=       mtab$m1a15296m_tmc.fits)>the HST components table
(instrum=       wfpc2)                Instrument represented by this pset
(Version=       14Feb94)              Date of Installation
(mode   =       a)
```

- Edit the parameters to enter new reference filenames and switch settings, based on recommendations from StarView, or from the WFPC2 reference file memo located at

  http://www.stsci.edu/ftp/instrument_news/WFPC2/Wfpc2_memos/wfpc2_reffiles.html

  When completed, type **:q**

- The screen will reappear, but this time, the fields will be blank except for the new entries. Verify that the changes are correct and enter additional changes if necessary. When completed, type **:q**

- A prompt will appear asking “**accept current parameters?**” with the options **no**, **yes**, and **abort**. If you wish to proceed in entering the new reference filenames and switches in the raw image header file (.d0h), type **yes**

Please refer to the STSDAS on-line help files *calwp2*, *ckwwfp2*, and *chcalpar* for more details.

How do I run *calwp2*?

- Before running *calwp2*, be sure that pointers to the location of reference files are set up properly. *uref$, ucal$,* and *mtab$* are pointers to directories where reference files are stored. They are prefixes to the calibration filenames specified in the image header. These pointers must be set before running *calwp2*.

  As an example, assume the raw data are located at /data/whimbrel1/science/, and *calwp2* will be run in that directory. And assume all reference files are located at /data/whimbrel1/ref/. In IRAF, set the pointers by typing

```
set uref = /data/whimbrel1/ref/
set ucal = /data/whimbrel1/science/
set mtab = /data/whimbrel1/ref/
```

  (Note: that final "/" is important! Don’t forget it.)

  You can verify that the pointers were set correctly by using the IRAF *show* command,

```
show uref
```

  gives

```
/data/whimbrel1/ref/
```

After doing this, running *calwp2* is easy. At the IRAF prompt, type

```
calwp2 u2g40o05t  ""
```

  In this example, the calibrated science data will have the same rootname as the raw science data, with the c0h/.c0d extension.

3.4 A Closer Look at the Calibration Process

What happens to the pixels at each stage of the calibration process?

The best way to understand the calibration process is to manually perform each step in the calibration pipeline, tracing a couple of pixels from the beginning to the end of the process. To do this, pick two unsaturated pixels in your raw science image, (x1,y1) and (x2,y2), and make a note of their raw data values, and location in their chip.

1. **Perform the mask correction**

   What are the new science data pixel values?

   Background: The static pixel mask reference file contains a map of permanently bad pixels. Currently, only two types of bad pixels are flagged: charge transfer traps (assigned the value 2) and pixels above charge transfer traps that are affected by the traps (assigned the value 256). This mask file is copied to the calibrated data quality file (.c1h, .c1d).

   Hint: The mask correction only updates the data quality file (.c1h, .c1d) with information about bad pixels. The science data is not changed. But be sure to check (x1,y1) and (x2,y2) to make sure they are not affected by the traps.

2. **Perform the A-to-D correction**

   What are the new science data pixel values?

   Background: Each CCD pixel absorbs energy from photons of light that impinge upon it, releasing electrons within the semiconductor. The accumulated electrons from a particular pixel are trapped in a specific location corresponding to that pixel. The analog-to-digital converter (ADC) is a device that converts the CCD pixel voltage signal (from trapped electrons) to Data Numbers (DNs) that can be stored in computer memory. For the WFPC2, the ADC has a range of 12 bits -- 4096 possible values ranging from 0 to 4095. In order to effectively “scale” the accumulated signal for storage, users can specify a ***gain*** of 7 electrons/DN or 14 electrons/DN. The choice of gain setting depends on the scientific objectives of the observations. (For more information, see the WFPC-2 Instrument Handbook (version 6.1), page 79-81, and for a general overview of CCDs, please refer to Electronic and Computer-aided Astronomy: From Eyes to Electronic Sensors, by Ian McLean.)

   The A-to-D converter has a known problem; certain DN values are reported more (or less) frequently than a perfect device. The A-to-D converter therefore produces small errors when converting from electrons to DN values. Although the “true” DN values can never be recovered, the errors are systematic and a statistical correction can be applied. (The largest correction for WFPC2 is 0.1%.)

   In theory, the A-to-D correction is a function of temperature. The A-to-D conversion reference file is a matrix of values for each chip; the first row contains possible temperature values for Bay 3. The second and subsequent rows, with each row corresponding to a particular temperature, contain A-to-D conversion corrections for each DN value between 0 to 4095.

   The example below illustrates the structure of an A-to-D converter correction file with conversion values for five different temperatures. The first row has 5 temperature values, t1 to t5. The second row has the DN corrections corresponding to temperature t1 -- there are 4096 columns, with the first column containing the correction value for a raw DN value of 0, and 4096th column containing the correction for the raw DN value of 4095. The third row has the corrections for temperature t2, the 4th row for temperature t3, etc.

	(col 1)	**(col 2)**	**(col 3)**	**(col 4)**	**(col 5)**	**. . . . . (col 4096)**
(row 1)	**----**	**t1**	**t2**	**t3**	**t4**	**t5**
(row 2)	**0_t1**	**1_t1**	**2_t1**	**3_t1**	**4_t1**	**. . . . . 4095_t1**
(row 3)	**0_t2**	**1_t2**	**2_t2**	**3_t2**	**4_t2**	**. . . . . 4095_t2**
(row 4)	**0_t3**	**1_t3**	**2_t3**	**3_t3**	**4_t3**	**. . . . . 4095_t3**
(row 5)	**0_t4**	**1_t4**	**2_t4**	**3_t4**	**4_t4**	**. . . . . 4095_t4**
(row 6)	**0_t5**	**1_t5**	**2_t5**	**3_t5**	**4_t5**	**. . . . . 4095_t5**

The A-to-D reference file was created from data taken during WFPC2 Thermal Vacumn tests before launch. On-orbit checks have determined that the conversion values have remained constant. Therefore, only the conversion values for a single temperature setting is necessary. Current reference files have the dimension 4096x2. Row 1 has one temperature entry, at [2,1], and all other values in row 1 are set to -1 (null value). Row two is the lookup table for this temperature, and has 4096 columns.

Example:

Determine the A-to-D correction for a DN value of 317 for the WF2 chip.

This correction can be found in group 2 of the A-to-D reference file, at location [317+1,2]. The task *listpix* can be used to obtain the correct DN value to be substituted in the calibrated data files (.c0h, .c0d).

```
listpix dbu1405iu.r1h[2][318,2]
```

```
1.  316.9859
```

During the A-to-D correction step in the calibration, all DN values of 317 in group 2 of the raw image data are changed to 316.9859.

3. **Perform the bias level correction**

What are the global bias values for even (BIASEVEN) and odd (BIASODD) columns?

What are the science data pixel values (x1,y1) and (x2,y2) after subtracting its global bias value?

Background: A pedestal of about 300 DN is introduced into the signal chain to prevent the occurrence of negative numbers. A mean value for this bias level can be obtained in the CCD overscan region stored in the engineering files (.x0d, .x0h) that accompanies each WFPC2 dataset.

(The overscan area is obtained as the CCD electronics continues to read-out even though there is no longer any physical correspondence to the chip.)

The mean bias value is slightly different for even and odd columns. During calibration, mean bias values are determined for the even and odd columns of the science image, derived using a subsection of the overscan region. These values are stored in the science image header keywords BIASEVEN and BIASODD, respectively. The mean bias levels are then subtracted from the science image; the BIASEVEN value from even columns of the science image, and the BIASODD value from the odd columns of the science image.

The mean bias levels are calculated from a subsection of the overscan image (.x0h,.x0d) at [9:14,10:790]. Columns 9, 11, and 13 in the overscan region are used to obtain the BIASEVEN value. Columns 10, 12, and 14 are used to derive a value for BIASODD. (This nomenclature, where odd columns in the engineering file are used to determine the mean bias level of even columns in the science image, and vice versa, is due to an offset between the overscan region and the image.)

Hints:

- Determine if (x1,y1) and (x2,y2) in the science image fall on even or odd columns.
- Determine the mean bias level for even and odd columns (BIASEVEN and BIASODD) for each chip, using the overscan region of that chip in the engineering file (.x0d, .x0h). Use a task like *imstat* to get mean values of the appropriate sections in the overscan image.
- Subtract the bias level (either BIASEVEN or BIASODD) from the value of the science data pixel, depending on whether the image pixel falls in an even or odd column.

4. **Perform a bias correction**

What are the pixel values in the bias correction file?

What are the new science data pixel values?

Background: After subtracting the global bias values from the image, there still remains small scale bias values that vary from pixel-to-pixel. These are removed by subtracting a bias correction reference image (.r2h, .r2d) from the science image. This bias reference file, or “superbias,” is generated annually using 120 individual bias frames that were corrected for A-to-D conversion errors, with global bias levels subtracted.

Hint: Look up the pixel values in the bias correction file (.r2h, .r2d) at positions (x1,y1) and (x2,y2). Subtract that bias correction value from the science data pixels.

5. **Perform a dark correction**

   What are the pixel values in the dark file?

   What are the new science data pixel values?

   Background: Thermally-induced dark currents, as well as a faint "glow" caused by cosmic rays striking the corrector plates, make dark corrections necessary for exposures greater than 10 seconds. This correction is done by subtracting a dark reference image from the science image.

   The dark reference image has two components: one is a "superdark" generated annually from 120 individual dark images. The second is hot pixel information derived from five darks taken during the week of the science observations. Therefore, a new dark reference file is generated every week using that year's superdark, but containing weekly-updated hot pixel information. If the data is retrieved shortly after the observations were taken, the dark reference file may be out-of-date by a couple of weeks. The user could either recalibrate the data with a new dark reference file when it becomes available, or re-request the data from the archive when the correct dark reference file is in the archive (which can be checked using StarView).

   Each dark reference image is normalized to a 1 second exposure time. Therefore, when it is applied to the science data, the dark file is first scaled to the science image by multiplying it with the DARKTIME keyword value in the raw science data header file (.d0h). (DARKTIME is defined as the total time from the start of an exposure to the beginning of readout. The pipeline approximates this "darktime" by setting it equal to the exposure time.)

   Hint: Look up the pixel values of (x1,y1) and (x2,y2) in the dark reference file. Remember that the dark file has been normalized to 1 second. Therefore, to correct for exposure time, look up the keyword DARKTIME in the raw image header file. Multiply the dark file pixel value by the DARKTIME value. Then, subtract the correctly-scaled dark value from the science data pixel value.

6. **Flat field the image**

   What are the pixel values in the flat field image?

   What are the new science data pixel values?

   Background: The photometric response in the science image varies over the field-of-view. There are several reasons for this effect. Each

CCD pixel has its own unique quantum efficiency. Each chip has a slightly different electronic gain. Large-scale vignetting of the field is caused by the telescope and WFPC2 mirrors, their support structures, and WFPC2 filters. Optical distortions are introduced by field flatteners in front of each chip, causing the sky area per pixel at a chip corner to be about 5% smaller than at the chip center. A manufacturing defect affecting every 34th row in the CCDs also reduces sky coverage per pixel. Even dust particles on the pyramid, CCD windows, and detectors cause artifacts. Most electronic effects were characterized during pre-launch thermal vacuum testing, while large-scale optical effects were determined from on-orbit Earth flats. The flat field file corrects for these sensitivity variations in the science image.

Hint: Look up the pixel values for (x1,y1) and (x2,y2) in the flat field file. Multiply the science pixel values with their corresponding flat field pixel values. (Note: The flat fields have been inverted to be consistent with other multiplicative reference files used in the pipeline calibration.)

7. **Shutter Shading Correction**

Was a shutter shading correction necessary for this dataset?

Background: The WFPC2 has two shutter blades. When an exposure begins, one shutter blade is moved off the light path. The exposure ends when the second shutter blade moves to block the light path. Although the blades move rapidly, their finite motion can cause exposure time variations over the field-of-view for total exposure times of 1 second or less. The calibration software automatically applies a shutter shading correction to images with total exposure times less than 10 seconds. The two shutters have slightly different speeds; therefore, there are two different correction files depending on which blade was moved out of the way at the beginning of the exposure.

Hint: Exposure times less than 10 seconds require a shutter shading correction. Below is an example of applying this correction using the IRAF task *imcalc*:

```
imcalc sci_image, shutter out_image “im1 * (1 + (im2 / <exposure time>))”
```

As a final check, compare the (x1,y1) and (x2,y2) values from the step-by-step calibration with the pixel values in the previously-calibrated images. Do they agree to 3 decimal places? If “no”, you may want to check your steps for errors.

4. Photometry: Converting DNs to a Magnitude

4.1 Some General Notes about WFPC2 Photometry

This section illustrates the use of aperture photometry to obtain V and I magnitudes of stars in the LMC star cluster NGC 2100. Other topics in photometry, such as PSF-fitting, surface, and narrow-band photometry, are not covered here. For more details on these topics, please refer to the following sources of information:

PSF-fitting Photometry:

Peter Stetson's DAOPHOT package can be found at

http://iraf.noao.edu/iraf/web/irafnews/dec94/dec94-S-27.html or
http://hires.gsfc.nasa.gov/~beck/pkgs/daophot2.html

Andrew Dolphin's HSTPhot, is specifically for WFPC2 data, and uses TinyTim PSFs at different locations on the WFPC2 chips.

http://www.noao.edu/staff/dolphin/hstphot/

DoPHOT, written by Mario Mateo, Abi Saha and Paul Schechter, searches for "objects", and produces positions, magnitudes, and crude classifications. The paper describing DoPHOT can be found at

http://adsbit.harvard.edu/cgi-bin/nph-iarticle_query?bibcode=1993PASP..105.1342S

The DoPHOT page is at

http://arcturus.mit.edu:80/~schech/dophot.html

Ken Mighell's MATPHOT does PSF-fitting CCD stellar photometry.

http://www.noao.edu/staff/mighell/matphot/

John Krist's Tiny Tim Software for creating simulated PSFs.

http://www.stsci.edu/software/tinytim/tinytim.html

Narrow-band Photometry:

FAQ located at

http://www.stsci.edu/instruments/wfpc2/Wfpc2_faq/wfpc2_nrw_phot_faq.html

Surface Photometry:

STSDAS has a software package for surface photometry called *isophote* (*stsdas.analysis.isophote*). Please refer to the on-line help files for more information on this method.

Useful aperture photometry links:

Photometry with the WFPC2 by Brad Whitmore

http://www.stsci.edu/instruments/wfpc2/wfpc2_doc.html#Phot

WFPC2 Photometry Cookbook by Brad Whitmore

http://www.stsci.edu/instruments/wfpc2/wfpc2_doc.html#Phot

The Photometric Performance and Calibration of WFPC2, by Holtzman, et al., 1995.

http://www.stsci.edu/instruments/wfpc2/wfpc2_doc.html#Phot

WFPC2 ISR 95-04: A Demonstration Analysis Script for Performing Aperture Photometry by Brad Whitmore and Inge Heyer

http://www.stsci.edu/instrument-news/isr/wfpc2/9504/9504_1.html

Ken Mighell's QDPHOT page.

http://www.noao.edu/noao/staff/mighell/qdphot/

CCDCAP: CCD Circular Aperture Photometry, also by Ken Mighell

http://www.noao.edu/noao/staff/mighell/ccdcap/

4.2 WFPC2 Photometric Systems

The magnitude is defined as

m= -2.5log10(DN/exptime) + zeropoint

where the zeropoint of an instrument, by definition, is the magnitude of an object that produces one count (or one DN) per second.

The zeropoint can be determined using four ways:

1. From your own ground-based photometry, using standard filters, of objects in the field (if available).
2. Using the zeropoints published by Jon Holtzman in The Photometric Performance and Calibration of WFPC2, PASP 1995, (a link to this paper can be found in http://www.stsci.edu/instruments/wfpc2/wfpc2_doc.html#Phot). These zeropoints are known as the WFPC2 Flight Photometric System. It was established to match the standard Johnson-Cousins UBVRI system such that the magnitudes of Vega in the standard U, B, V, R, and I filters are the same as the magnitudes in the closest equivalent WFPC2 filters (F336W, F439W, F555W, F675W, and F814W respectively).

   Holtzman et al. also provides transformation coefficients to convert the WFPC2 Flight Photometric System to standard UBVRI magnitudes, but warns that the transformations can be highly uncertain. Updated photometric zeropoints have recently been provided by Andrew Dolphin, and can be found on his website at http://www.noao.edu/staff/dolphin/wfpc2_calib/. Note: Both Holtzman and Dolphin zeropoints are applied to magnitudes in an aperture radius of 0.5".

3. Another set of zeropoints was published by Whitmore and Heyer in Instrument Science Report 96-04, and later updated in the HST Data Handbook. (Future zeropoints updates will be announced in the WFPC2 Space Telescope Analysis Newsletter (STAN) and posted on the WFPC2 website. These zeropoints are defined such that Vega has a magnitude of zero for all WFPC2 filters. Note: these zeropoints are applied to magnitudes in an "infinite" aperture, which is defined as the magnitude in a 0.5" aperture - 0.1 magnitude.

   The magnitude of Vega in the Holtzman system, and in the system originally defined by Whitmore and Heyer, are summarized in the table below:

WFPC2 Flight Photometric System (Holtzman et al. ’95)		Whitmore-Heyer System	
U(Johnson-Cousins)=0.02	F336W(WFPC2 Flight)=0.02	U(Vegamag)=0	F336W(Vegamag)=0
B(Johnson-Cousins)=0.02	F439W(WFPC2 Flight)=0.02	B(Vegamag)=0	F439W(Vegamag)=0
V(Johnson-Cousins)=0.03	F555W(WFPC2 Flight)=0.03	V(Vegamag)=0	F555W(Vegamag)=0
R(Johnson-Cousins)=0.039	F675W(WFPC2 Flight)=0.039	R(Vegamag)=0	F675W(Vegamag)=0
I (Johnson-Cousins)=0.035	F814W(WFPC2 Flight)=0.035	I (Vegamag)=0	F814W(Vegamag)=0

4. The PHOTFLAM image header keyword value is the flux of a source with constant flux per unit wavelength (in ergs s-1 cm-2 A-1) that produces a count rate of 1 DN per second. This keyword is useful for converting the counts directly to a flux density, or to a flux-based system such as the *AB system* or the *STMAG system*. Please refer to the WFPC2 HST Data Handbook for more details.

4.3 From DNs to Instrument Magnitudes: A Photometry Demo

The following sections illustrate one of several different stellar aperture photometry methods. It is by no means a standard technique, but instead, an introduction that will provide a foundation for exploring different types of stellar photometry methods.

This example is a step-by-step procedure for measuring the magnitudes of stars in the NGC 2100 field in the PC, using filters F555W and F814W. The datasets used are

F555W: u5ay0701r, u5ay0702r
F814W: u5ay0704r, u5ay0705r

Place the images in two separate directories, one for each filter. First of all, get some basic information about these image, such as exposure time, A-to-D gain, and filters used:

```
hselect "u5ay0701r.c0h, u5ay0702r.c0h" $I,exptime,atodgain,filtnam1,filtnam2 yes

u5ay0701r.c0h   3.500000000000E+02     7.0    F555W
u5ay0702r.c0h   3.500000000000E+02     7.0    F555W
```

```
hselect "u5ay0704r.c0h, u5ay0705r.c0h" $I,exptime,atodgain,filtnam1,filtnam2 yes

u5ay0704r.c0h   3.500000000000E+02     7.0    F814W
u5ay0705r.c0h   3.500000000000E+02     7.0    F814W
```

In this example, the aperture photometry task *apphot* will be used. This package is available in IRAF. It can be loaded by typing

```
noao
digiphot
apphot
```

4.3.1 Combine the Image Pairs

Determine if the image pairs for each filter are registered. This can be done by blinking the images, or by measuring the position of several stars (using *imexam*) in each image to verify that their coordinates are identical. In general, consecutive observations with the same pointing using the same guide stars will show no offsets. But if the exposure is long, and one of the Fine Guidance Sensors loses track of its guide star, a small drift in the telescope roll is possible, resulting in a slightly trailed image. Such problems are always documented in the data quality reports (.pdq files) that accompany each dataset, retrievable from the archive.

The images have the same pointing, and we will use the task *crrej* to combine the images. (Other available tasks for WFPC2 image combination are s*tsdas.hst_calib.wfpc.combine* and *stsdas.toolbox.imgtools.gcombine*.)

First, save a copy of the data quality files (.c1h, .c1d) because *crrej* will change some values when it flags cosmic rays (with ID=128). Then, combine the images. Be sure to use the correct setting for the A-to-D gain and readnoise (in DN) parameters. Otherwise, default settings have been used for other parameters in this example.

In the F555W directory:

```
!mkdir backup_dq
!cp *.c1h *.c1d backup_dq/
unlearn crrej
crrej "u5ay0701r.c0h,u5ay0702r.c0h" f555w_temp.hhh \
"u5ay0701r.c0h,u5ay0702r.c0h" "8,6,4" atodgain=7 readnoise=0.72 crdqval=128
```

In the F814W directory:

```
!mkdir backup_dq
!cp *.c1h *.c1d backup_dq/
unlearn crrej
crrej "u5ay0704r.c0h,u5ay0705r.c0h" f814w_temp.hhh \
"u5ay0704r.c0h,u5ay0705r.c0h" "8,6,4" atodgain=7 readnoise=0.72 crdqval=128
```

Note: Many WFPC2 images are now dithered to remove hot pixels and to obtain better pixel resolution. For more information on how to reduce dithered images, please refer to the Dither Handbook, edited by Anton Koekemoer, located at

http://www.stsci.edu/instruments/wfpc2/Wfpc2_driz/dither_handbook.html.

4.3.2 Correct the Images for Geometric Distortion

The WFPC2 camera optics introduces a geometric distortion to the field that affects astrometry and photometry. The affect on surface photometry is removed in the pipeline when the images are multiplied by flat fields. But for point source photometry, a correction needs to be applied as a function of the position of the object in the field. (For more information, please refer to the paper by Holtzman et al., Performance and Calibration of WFPC2 on the Hubble Space Telescope, especially Figure 16.) A geometric correction image (for all four chips) was generated by the WFPC2 Instrument Development Team, called f1k155bu.r9h, that can be retrieved from the photometry section of the WFPC2 home page at

http://www.stsci.edu/instruments/wfpc2/Wfpc2_memos/wfpc2_reffiles.html#Pixel

Note: There is a wavelength dependence in the distortion in the UV. Details regarding corrections for other filters can be found in the paper “Geometry of the WFPC2 Focal Plane” by Trauger et al. in Calibrating Hubble Space Telescope: Post Servicing Mission, a Workshop held on May 15 - 17, 1995 (contact help@stsci.edu to request a paper copy). A new geometric distortion solution for F555W is also available: please see ISR 2001-10: An Improved Geometric Solution for WFPC2 by Casertano and Wiggs.

The simplest way to apply this correction is to multiply your image by f1k155bu.r9h. In the F555W directory,

```
imcalc "f555w_temp.hhh,f1k1552bu.r9h" f555w.hhh "im1*im2"
```

In the F814W directory,

```
imcalc "f814w_temp.hhh,f1k1552bu.r9h" f814w.hhh "im1*im2"
```

4.3.3 Create a Coordinate List for the Stars

Since the F555W and F814W images were obtained at the same pointing, one coordinate list will be used. This coordinate list will be generated using the task *daofind*, which is part of the *apphot* aperture photometry package in IRAF located at *noao.digiphot.apphot*. The *daofind* task also calls two subtasks known as parameter sets (or psets): *datapars* and *findpars*.

Using selection criteria defined by the task parameters, *daofind* automatically identifies stars in an image, writing each star's x-y positions to a list.

In this example, default values are used, except for the parameters *findpars.threshold*, *datapars.sigma*, and *datapars.fwhmpsf.*

The default parameters for *daofind* are listed below:

```
image =                      Input image
(output = "default")         Results file
(starmap = "")               Output density enhancement image
(skymap = "")                Output sky image
(datapars = "")              Data dependent parameters
(findpars = "")              Object detection parameter
(boundary = "nearest")       Boundary extension (constant, nearest, reflect,
(constant = 0.)              Constant for boundary extension
(interactive = no)           Interactive mode
(verify = yes)               Verify critical parameters in non-interactive m
(update = no)                Update critical parameters in non-interactive m
(verbose = no)               Print messages in non-interactive mode
(graphics = "stdgraph")      Graphics device
(display = "stdimage")       Display device
(icommands = "")             Image cursor: [x y wcs] key [cmd]
(gcommands = "")             Graphics cursor: [x y wcs] key [cmd]
(mode = "ql")
```

There are two parameter sets (psets) in *daofind*, *datapars* and *findpars*:

datapars:

(scale = 1.)	Image scale in units per pixel
(fwhmpsf = 2.5)	FWHM of the PSF in scale units
(emission = yes)	Features are positive ?
(sigma = INDEF)	Standard deviation of background in counts
(datamin = INDEF)	Minimum good data value
(datamax = INDEF)	Maximum good data value
(noise = "poisson")	Noise model
(ccdread = "")	CCD readout noise image header keyword
(gain = "")	CCD gain image header keyword
(readnoise = 0.)	CCD readout noise in electrons
(epadu = 1.)	Gain in electrons per count
(exposure = "")	Exposure time image header keyword
(airmass = "")	Airmass image header keyword
(filter = "")	Filter image header keyword
(obstime = "")	Time of observation image header keyword
(itime = 1.)	Exposure time
(xairmass = INDEF)	Airmass
(ifilter = "INDEF")	Filter
(otime = "INDEF")	Time of observation
(mode = "ql")	

findpars:

(threshold = 4.)	Threshold in sigma for feature detection
(nsigma = 1.5)	Width of convolution kernel in sigma
(ratio = 1.)	Ratio of minor to major axis of Gaussian kernel
(theta = 0.)	Position angle of major axis of Gaussian kernel
(sharplo = 0.2)	Lower bound on sharpness for feature detection
(sharphi = 1.)	Upper bound on sharpness for feature detection
(roundlo = -1.)	Lower bound on roundness for feature detection
(roundhi = 1.)	Upper bound on roundness for feature detection
(mkdetections = no)	Mark detected stars on the display ?
(mode = "ql")	

Three parameters define the faint limit of stars found by *daofind*. They are *datapars.fwhmpsf*, *datapars.sigma*, and *datapars.fwhmpsf*.

1. The parameter *datapars.fwhmpsf* is the full-width-at-half-max (FWHM) of the point spread function. This value can be measured on the image using *imexamine* (use the *r* key -- the FWHM is the last value on line 2 that's printed on the screen). Measure the FWHM of a few stars with a high signal-to-noise ratio, and use the average FWHM of those stars as the value for *datapars.fwhmpsf*. In this example, the average FWHM was found to be about 1.48 pixels.

   The *datapars.sigma* value is the sky standard deviation in the image. Use *imstatistics* to measure a few clean areas in the image, and use the average of those sky standard deviations as the value of *datapars.sigma*. In this image, the mean standard deviation for the sky was about 1.53 DN.

The object threshold detection parameter, *threshold* (in units of *sigma)*, defines the lowest flux limit for selecting objects in *daofind*.

To determine a cut-off for selecting faint objects, two criteria are needed. First, the object must have a FWHM close to the value in *datapars.fwhmpsf*. Second, the value of *threshold* needs to be determined. *daofind* looks for objects using this criteria:

object’s peak flux value > (*findpars.threshold * datapars.sigma)*

One starting point is to get the average measurement of the brightest pixel in several of the faintest stars to be used in photometry measurements. Define that average value to be the minimum flux value to be detected by *daofind*, and calculate the *threshold*, where

threshold = *sigma* / (minimum flux value).

In this example, the brightest pixel in several faint stars were around 40 DN. Therefore, the *threshold* = *sigma* / 40 = 40./1.53 = 26 ~ 30.

Create a list of stars and their positions on the chip, using *daofind*:

```
daofind f555w.hhh[1] output=pc_tmp1.pos  scale=1 \
fwhmpsf=1.48 sigma=1.53 threshold=30 verify=no interact=no
```

The file pc_tmp1.pos contains seven columns, where the 1st and 2nd columns are the object’s x-y coordinates.

Display the image, then mark the stars found by *daofind*, using the task *tvmark*. (The *mark* and *radii* parameters define a circle of radius 5 pixels.)

```
display f555w.hhh[1] 1
tvmark 1 pc_tmp1.pos mark=circle radii=5
```

You’ll notice that many false objects were found along the pyramid edges. To eliminate them, remove all objects where x <= 60 and y <= 70. In the coordinate list, create a new column (the 8th column) that will set an initial flag=0 for "bad" objects.

```
tcalc pc_tmp1.pos c8 "0"
```

Using *tcalc* again, reset the flags so that the objects not on the pyramid edges are set to 1. This leaves objects within x <= 60 and y <= 70 unchanged (value of 0).

```
tcalc pc_tmp1.pos c8 "if (c1 <= 60) then 1 else c8"
tcalc pc_tmp1.pos c8 "if (c2 <= 70) then 1 else c8"
```

Keep all objects that are not on the pyramid edges (flagged as 1) to create a final position list, pc.pos.

```
tsel pc_tmp1.pos pc.pos "c8 .ne. 1"
```

4.3.4 Run the *phot* Task to get the Flux of the Stars, and Evaluate the Quality of the Results

The *phot* task (part of the *noao.digiphot.apphot* package) will be used to run aperture photometry on the list of stars created in the previous section. Listed below are the default parameters for *phot*.

```
image = ""                  Input image
skyfile = ""                Sky file
(coords = "")               Coordinate list
(output = "default")        Results file
(plotfile = "")             File of plot metacode
(datapars = "")             Data dependent parameters
(centerpars = "")           Centering parameters
(fitskypars = "")           Sky fitting parameters
(photpars = "")             Photometry parameters
(interactive = yes)         Mode of use
(radplots = no)             Plot the radial profiles in interactive mode
(verify = yes)              Verify critical parameters in non-interactive m
(update = no)               Update critical parameters in non-interactive m
(verbose = no)              Print messages in non-interactive mode
(graphics = "stdgraph")     Graphics device
(display = "stdimage")      Display device
(icommands = "")            Image cursor: [x y wcs] key [cmd]
(gcommands = "")            Graphics cursor: [x y wcs] key [cmd]
(mode = "ql")
```

The *phot* task calls these psets: *datapars*, *centerpars*, *fitskypars*, and *photpars*.

datapars - Edit the data dependent parameters (*noao.digiphot.apphot*)
centerpars -Edit the centering parameters (*noao.digiphot.appho*t)
fitskypars - Edit the sky fitting parameters (*noao.digiphot.apphot*)
photpars - Edit the photometry parameters (*noao.digiphot.apphot*)

The default values for *datapars* are the same values used in running *daofind*.

Default values for *centerpars*:

(calgorithm = "centroid")	Centering algorithm
(cbox = 5.)	Centering box width in scale units
(cthreshold = 0.)	Centering threshold in sigma above background
(minsnratio = 1.)	Minimum signal-to-noise ratio for centering alg
(cmaxiter = 10)	Maximum number of iterations for centering algo
(maxshift = 1.)	Maximum center shift in scale units
(clean = no)	Symmetry clean before centering ?
(rclean = 1.)	Cleaning radius in scale units
(rclip = 2.)	Clipping radius in scale units
(kclean = 3.)	Rejection limit in sigma
(mkcenter = no)	Mark the computed center on display ?

Default values for *fitskypars*:

(salgorithm = "centroid")	Sky fitting algorithm
(annulus = 10.)	Inner radius of sky annulus in scale units
(dannulus = 10.)	Width of sky annulus in scale units
(skyvalue = 0.)	User sky value
(smaxiter = 10)	Maximum number of sky fitting iterations
(sloclip = 0.)	Lower clipping factor in percent
(shiclip = 0.)	Upper clipping factor in percent
(snreject = 50)	Maximum number of sky fitting rejection iterati
(sloreject = 3.)	Lower K-sigma rejection limit in sky sigma
(shireject = 3.)	Upper K-sigma rejection limit in sky sigma
(khist = 3.)	Half width of histogram in sky sigma
(binsize = 0.1)	Binsize of histogram in sky sigma
(smooth = no)	Boxcar smooth the histogram
(rgrow = 0.)	Region growing radius in scale units
(mksky = no)	Mark sky annuli on the display

Default values for *photpars*:

(weighting = "constant")	Photometric weighting scheme for wphot
(apertures = "3.")	List of aperture radii in scale units
(zmag = 25.)	Zero point of magnitude scale
(mkapert = no)	Draw apertures on the display

In this example, default values are retained for most parameters. Only those unique to the data are changed. These parameters are:

photpars.zmag -- The zeropoints for F555W and F814W in the PC, the values being 21.734 and 20.827, respectively. These are the latest values (as of May 1, 2002) obtained from Andrew Dolphin's website (http://www.noao.edu/staff/dolphin/wfpc2_calib/).

photpars.apertures -- the photometry aperture radius is set to 2 pixels because about 80% of the light from the star is located within a 2-pixel radius from the star’s center. Later, photometry values will be adjusted for an infinite aperture.

fitskypars.annulus & *fitskypars.dannulus* -- these values are set to 4 and 7 pixels respectively. The sky is computed using an annulus around the sky within 4 pixels to 7 pixels from the star’s center.

fitskypars.salgorithm -- According to ISR 96-03: Background Subtraction in WFPC2 Frames by Harry Ferguson (available at http://www.stsci.edu/instruments/wfpc2/Wfpc2_isr/wfpc2_isr9603.html), the most reliable algorithm for determining the background is by setting *salgorithm* to either *centroid* or *ofilter.*

datapars.readnoise -- This is the CCD readout noise in electrons. The images in this example were created by combining two images using *crrej*. The readout noise for each single image is 5 electrons. For two combined images where the algorithm creates an additive output (not normalized to an average), the readnoise becomes $\sqrt{5^2 + 5^2}$ = 7.07 electrons.

datapars.epadu -- The gain in electrons per count. For these images, the gain is 7 electrons per DN. (Note: The gain remains at 7 because the images were "added" in *crrej*, and the exposure time parameter was updated. If another image-combining task had been used to obtain the average of the two images, the gain should be set to 7 * 2 = 14.)

centerpars.calgorithm -- This parameter determines if the star should be centered before its flux is measured. In this example, we have chosen not to change the original coordinates so the non-default value of "none" is used.

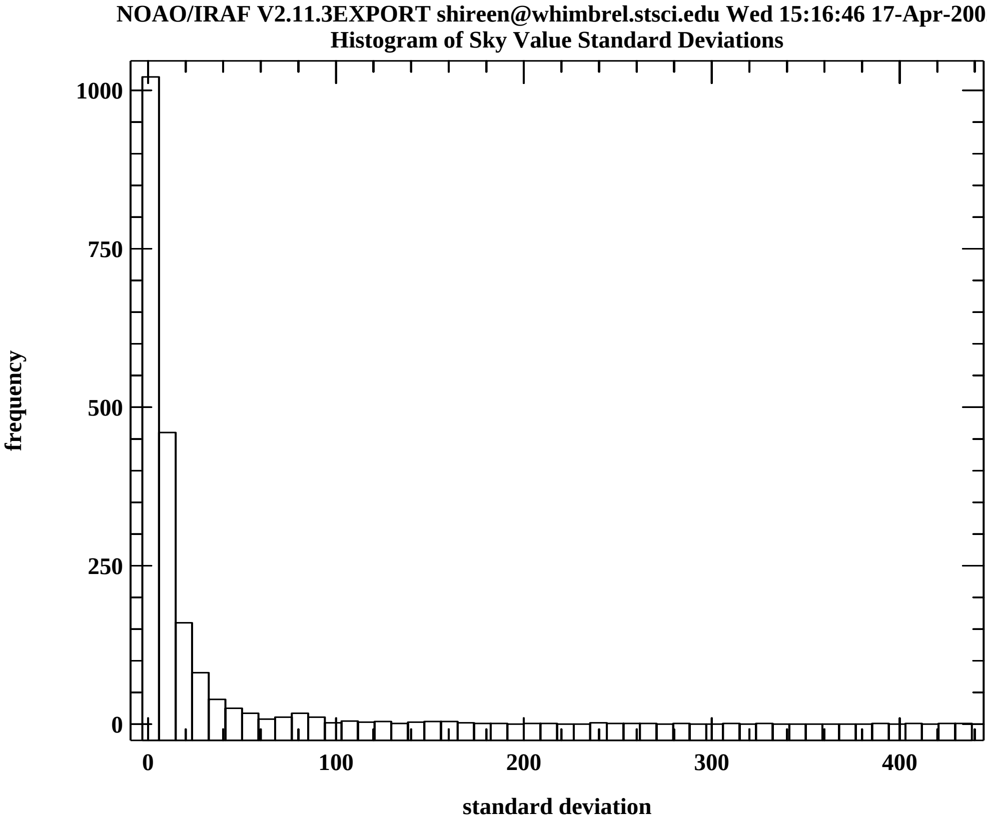
In the script below, the *phot* task is run on the combined image, f555w.hhh[1]. Flux values for each star are piped to a text file, then converted to an IRAF table. The quality of each measurement is then assessed, and bad data is thrown out.

```
# For F555W:
# <begin script>
# Run the phot task on f555w.hhh[1] for the list of stars generated using daofind.
# Write the values to a temporary file called temp1.

unlearn phot
unlearn datapars
unlearn centerpars
unlearn fitskypars
unlearn photpars
phot f555w.hhh[1] "" coords=pc.pos output=temp1 zmag=22.461 \
aperture=2 salgori=ofilter annulus=4 dannu=7 exposure=exptime \
readnoi=7.1 epadu=7 calgorithm=none interac=no verify=no
```

```
# Write some of the important values to a file called temp2 using the task txdump.
# The values needed are ID,XCENTER,YCENTER,MSKY,STDEV,SSKEW,NSKY,
# NSREJ,FLUX,MAG,MERR where
# ID = star identification number provided by daofind
# XCENTER, YCENTER = the x,y position of the star
# MSKY = best estimate of the sky value (per pixel)
# STDEV = standard deviation of the sky
# SSKEW = skew of sky measurement
# NSKY = number of sky pixels
# NSREJ = number of sky pixels rejected respectively
# FLUX = Source counts without sky subtraction in the aperture
# MAG =  magnitude of star using the specified aperture
# MERR = error in magnitude

txdump temp1 \
"ID,XCENTER,YCENTER,MSKY,STDEV,SSKEW,NSKY,NSREJ,FLUX,MAG,
MERR" \
yes > temp2

# Convert the text file temp2 to a table using the task tcreate. A file describing
# the format of each column is a required input for tcreate.

# Create a format file called f555w_format
print "f5_id    i" > f555w_format
print "f5_x     r" >> f555w_format
print "f5_y     r" >> f555w_format
print "f5_msky  r" >> f555w_format
print "f5_stdev r" >> f555w_format
print "f5_sskew r" >> f555w_format
print "f5_nsky  r" >> f555w_format
print "f5_nsrej r" >> f555w_format
print "f5_flux  r" >> f555w_format
print "f5_mag   r" >> f555w_format
print "f5_merr  r" >> f555w_format

#(Note: r and i in the format file above refer to real and integer numbers respectively.)
# Create the table using tcreate
tcreate f555w_pc f555w_format temp2

# Since this is a very crowded field, some stars need to be removed. They include
# stars affected by very close "companions" and/or are in very busy regions where
# accurate photometry measurements are not possible. This can be done by looking
# at the sky scatter, contained in the column STDEV, the  sky value standard
# deviation.
# Create a histogram of the sky value standard deviations to see what the
# distribution looks like, and plot the results using sgraph.
```

```
thist  f555w_pc STDOUT f5_stdev nbins=50 | sgraph crvstyle=fullhist \
xlabel="standard deviation" ylabel="frequency" \
title= "Histogram of Sky Value Standard Deviations"
```

Figure 8: Histogram showing the sky value standard deviations.



# This is a really big list of stars. From inspecting the histogram numbers, most
# of the stars appear to have a standard deviation less than and equal to 20. So we
# will ignore stars with sky standard deviations greater than 20 from here on.

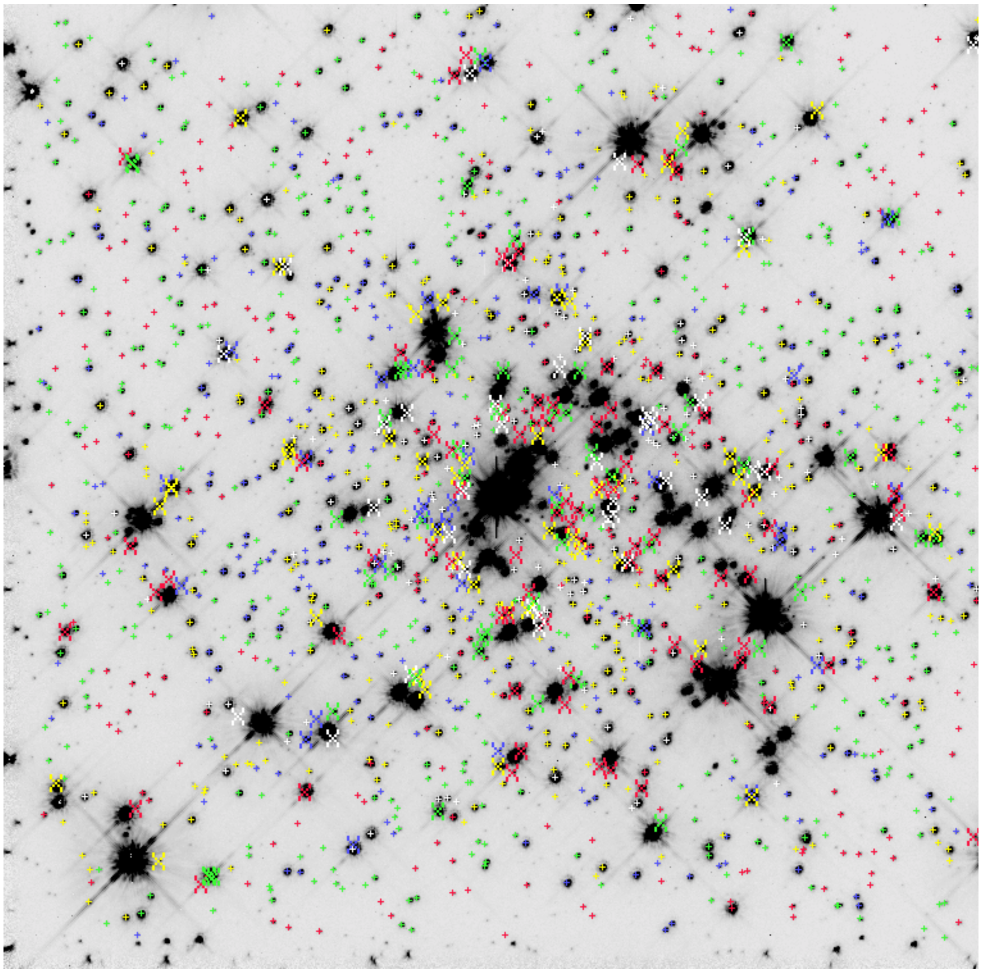
# To see how the sky standard deviation is distributed across the image, create tables
# containing a range of sky standard deviation values.

# First create a table for each range of standard deviation.

```
tsel f555w_pc f5_stdev_2  "f5_stdev .le. 2"
tsel f555w_pc f5_stdev_3  "f5_stdev .gt. 2  && f5_stdev .le. 3"
tsel f555w_pc f5_stdev_4  "f5_stdev .gt. 3  && f5_stdev .le. 4"
tsel f555w_pc f5_stdev_5  "f5_stdev .gt. 4  && f5_stdev .le. 5"
tsel f555w_pc f5_stdev_6  "f5_stdev .gt. 5  && f5_stdev .le. 6"
tsel f555w_pc f5_stdev_7  "f5_stdev .gt. 6  && f5_stdev .le. 7"
tsel f555w_pc f5_stdev_8  "f5_stdev .gt. 7  && f5_stdev .le. 8"
tsel f555w_pc f5_stdev_9  "f5_stdev .gt. 8  && f5_stdev .le. 9"
tsel f555w_pc f5_stdev_10 "f5_stdev .gt. 9  && f5_stdev .le. 10"
tsel f555w_pc f5_stdev_11 "f5_stdev .gt. 10 && f5_stdev .le. 11"
tsel f555w_pc f5_stdev_12 "f5_stdev .gt. 11 && f5_stdev .le. 12"
tsel f555w_pc f5_stdev_13 "f5_stdev .gt. 12 && f5_stdev .le. 13"
tsel f555w_pc f5_stdev_14 "f5_stdev .gt. 13 && f5_stdev .le. 14"
tsel f555w_pc f5_stdev_15 "f5_stdev .gt. 14 && f5_stdev .le. 15"
tsel f555w_pc f5_stdev_16 "f5_stdev .gt. 15 && f5_stdev .le. 16"
tsel f555w_pc f5_stdev_17 "f5_stdev .gt. 16 && f5_stdev .le. 17"
tsel f555w_pc f5_stdev_18 "f5_stdev .gt. 17 && f5_stdev .le. 18"
tsel f555w_pc f5_stdev_19 "f5_stdev .gt. 18 && f5_stdev .le. 19"
tsel f555w_pc f5_stdev_20 "f5_stdev .gt. 19 && f5_stdev .le. 20"

# Dump the x,y positions in the tables above into ascii files.
tprint.showrow=no
tprint.showhdr=no
tprint.showunits=no
tprint f5_stdev_2 columns="f5_x,f5_y"   > f5_stdev_2.pos
tprint f5_stdev_3 columns="f5_x,f5_y"   > f5_stdev_3.pos
tprint f5_stdev_4 columns="f5_x,f5_y"   > f5_stdev_4.pos
tprint f5_stdev_5 columns="f5_x,f5_y"   > f5_stdev_5.pos
tprint f5_stdev_6 columns="f5_x,f5_y"   > f5_stdev_6.pos
tprint f5_stdev_7 columns="f5_x,f5_y"   > f5_stdev_7.pos
tprint f5_stdev_8 columns="f5_x,f5_y"   > f5_stdev_8.pos
tprint f5_stdev_9 columns="f5_x,f5_y"   > f5_stdev_9.pos
tprint f5_stdev_10 columns="f5_x,f5_y"  > f5_stdev_10.pos
tprint f5_stdev_11 columns="f5_x,f5_y"  > f5_stdev_11.pos
tprint f5_stdev_12 columns="f5_x,f5_y"  > f5_stdev_12.pos
tprint f5_stdev_13 columns="f5_x,f5_y"  > f5_stdev_13.pos
tprint f5_stdev_14 columns="f5_x,f5_y"  > f5_stdev_14.pos
tprint f5_stdev_15 columns="f5_x,f5_y"  > f5_stdev_15.pos
tprint f5_stdev_16 columns="f5_x,f5_y"  > f5_stdev_16.pos
tprint f5_stdev_17 columns="f5_x,f5_y"  > f5_stdev_17.pos
tprint f5_stdev_18 columns="f5_x,f5_y"  > f5_stdev_18.pos
tprint f5_stdev_19 columns="f5_x,f5_y"  > f5_stdev_19.pos
tprint f5_stdev_20 columns="f5_x,f5_y"  > f5_stdev_20.pos

# Display the image, then plot the coordinates in each file. Use a different color for
# each sky standard deviation range. For instance, all standard deviation values less
# than 2 are represented by red "plus" signs.
```

```
disp f555w.hhh  1


# Sky standard deviation values between 1 and 10 are considered to be in the
#  "good" range. (This is an arbitrary cut-off point. It’s important to inspect the plots
# on the image to see if it makes sense.)
tvmark 1 f5_stdev_2.pos mark=plus txsize=1 color=204 #red
tvmark 1 f5_stdev_3.pos mark=plus txsize=1 color=205 #green
tvmark 1 f5_stdev_4.pos mark=plus txsize=1 color=206 #blue
tvmark 1 f5_stdev_5.pos mark=plus txsize=1 color=207 #yellow
tvmark 1 f5_stdev_6.pos mark=plus txsize=1 color=210 #coral
tvmark 1 f5_stdev_7.pos mark=plus txsize=1 color=211 #maroon
tvmark 1 f5_stdev_8.pos mark=plus txsize=1 color=213 #khaki
tvmark 1 f5_stdev_9.pos mark=plus txsize=1 color=215 #turquoise
tvmark 1 f5_stdev_10.pos mark=plus txsize=1 color=217 #wheat


# Sky standard deviation values between 11 and 20 are considered to be in
# the "questionable" range.
tvmark 1 f5_stdev_11.pos mark=cross txsize=2 color=204 #red
tvmark 1 f5_stdev_12.pos mark=cross txsize=2 color=205 #green
tvmark 1 f5_stdev_13.pos mark=cross txsize=2 color=206 #blue
tvmark 1 f5_stdev_14.pos mark=cross txsize=2 color=207 #yellow
tvmark 1 f5_stdev_15.pos mark=cross txsize=2 color=210 #coral
tvmark 1 f5_stdev_16.pos mark=cross txsize=2 color=211 #maroon
tvmark 1 f5_stdev_17.pos mark=cross txsize=2 color=213 #khaki
tvmark 1 f5_stdev_18.pos mark=cross txsize=2 color=215 #turquoise
tvmark 1 f5_stdev_19.pos mark=cross txsize=2 color=217 #wheat
tvmark 1 f5_stdev_20.pos mark=cross txsize=2 color=214 #orchid


# <end script>
```

Figure 9: An overplot of standard deviation value markers over their associated stars.



An inspection of the plot show that stars with minimal sky scatter mostly appear to be outside the bright central area that is dominated by scattered light from very bright stars. The stars in this range appear to be unsaturated objects, ranging from moderately faint to moderately bright. Stars with large sky standard deviation values appear to be excessively bright, have prominent diffraction spikes, or have other close stellar objects in the field.

Using the star list generated for the f555w.hhh image, obtain photometry for those same objects in the f814w.hhh image.

# <begin script>
# Run the *phot* task on f814w.hhh[1] and write the values to a temporary file
# called temp1.

unlearn phot

unlearn datapars

unlearn centerpars

unlearn fitskypars

unlearn photpars

```
phot f814w.hhh[1] "" coords=pc.pos output=temp1 zmag=21.587 \
aperture=2 salgori=ofilter annulus=4 dannu=7 exposure=exptime \
readnoi=7.1 epadu=7 calgorithm=none interac=no verify=no


# Write the important values to a file called temp2 using the task txdump.
# The values:
# ID,XCENTER,YCENTER,MSKY,STDEV,SSKEW,NSKY,NSREJ,FLUX,
# MAG,MERR
# ID = star identification number from daofind
# XCENTER, YCENTER = the x,y position of the star
# MSKY = best estimate of the sky value (per pixel)
# STDEV = standard deviation of the sky
# SSKEW = skew of sky measurement
# NSKY = number of sky pixels
# NSREJ = number of sky pixels rejected respectively
# FLUX = counts within the aperture
# MAG =  magnitude of star using the specified aperture
# MERR = error in magnitude
txdump temp1 \
"ID,XCENTER,YCENTER,MSKY,STDEV,SSKEW,NSKY,NSREJ,FLUX,MAG,
MERR" \
yes > temp2


# Convert the text file temp2 to a table using the task tcreate. A file describing
# the format of each column is a required input for tcreate.

# Create a format file called f814w_format
print "f8_id    i" > f814w_format
print "f8_x     r" >> f814w_format
print "f8_y     r" >> f814w_format
print "f8_msky  r" >> f814w_format
print "f8_stdev r" >> f814w_format
print "f8_sskew r" >> f814w_format
print "f8_nsky  r" >> f814w_format
print "f8_nsrej r" >> f814w_format
print "f8_flux  r" >> f814w_format
print "f8_mag   r" >> f814w_format
print "f8_merr  r" >> f814w_format


# Create the table using tcreate
tcreate f814w_pc f814w_format temp2
```

4.4 Corrections to the Instrument Magnitudes

The following corrections are needed:

1. Aperture Correction from aperture radius = 2 pixels to radius = 10.87 pixels (0.5"). This is needed for use in the CTE equation.
2. Computing CTE-corrected Magnitudes.
3. Contamination correction (only significant for UV observations. It won't be applied to this dataset, but an example will be provided on how it's done.)

Later, after calculating the standard magnitudes, yet another aperture correction will be done, from an aperture radius of 0.5" to an infinite radius.

4.4.1 Aperture Correction from Aperture Radius of 2 Pixels to 10.87 Pixels.

The WFPC2 was found, shortly after launch, to have a charge transfer efficiency (CTE) problem; objects appeared about 10% fainter at the top of the chip (at y=800), when compared to the bottom of the chip (at y=0). This CTE problem is getting worse with time. For faint objects with low backgrounds, the loss can now be up to 50% over the chip. (see ISR 01-09: The WFPC2 Photometric CTE Monitor, Heyer at http://www.stsci.edu/instruments/wfpc2/Wfpc2_isr/wfpc2_isr0109.html.)

The operating temperature of the CCDs was reduced from -76^{o}C to -88^{o}C on April 23 '94. After this cool-down, the flux differences due to CTE were reduced to about 4%. CTE effects in warmer temperature data have not been well characterized.

CTE has been well-characterized for data taken at the standard -88^{o}C operating temperature. The equations for WF2, WF3, and WF4 measurements, at 2 and 5 aperture radii, were first documented in Instrument Science Report 97-08, New Results on Charge Transfer Efficiency and Constraints on Flat-Field Accuracy by Whitmore and Heyer, located at http://www.stsci.edu/instruments/wfpc2/Wfpc2_isr/wfpc2_isr9708.html. It showed that CTE depends on five parameters: target brightness, background, date of observation, as well as *x* and *y* position on the chip. The time dependency aspect of CTE was updated to the Whitmore-Heyer CTE equations in a 1998 memo, also found at the above-mentioned website. Additional information about WFPC2 CTE can be found in a paper titled "Charge-Transfer Efficiency of WFPC2" by Whitmore, et al., Publications of the Astronomical Society of the Pacific, 111:1559-1576, 1999 December.

Since the publication of the above-mentioned papers, there have been improvements to the equations characterizing CTE. In this document, we use the current-best equations developed by Andrew Dolphin of NOAO. Information about the Dolphin CTE equations can be found in his paper, The Charge-Transfer Efficiency and Calibration of WFPC2, Publications of the Astronomical Society of the Pacific, 112:1397-1410, 2000 October. The equations used in this document are the currently best-available CTE equations (as of May 1, 2002), obtained from http://www.noao.edu/staff/dolphin/wfpc2_calib/. Work in characterizing WFPC2 CTE continues to be actively pursued by several people, and updates will be made available on the WFPC2 webpage.

CTE Corrections using Andrew Dolphin's CTE Equations

The equations used in this section were taken from Andrew Dolphin's webpage at http://www.noao.edu/staff/dolphin/wfpc2_calib/ in May 2002. He is continually updating the equations as he gets better results, so please visit that website for the latest information.

In this example, stars were measured using an aperture radius of 2 pixels. The Dolphin CTE equations assume an aperture of 0.5". Therefore, a flux aperture correction has to be derived from an aperture radius of 2 pixels to an aperture radius of 0.5". Since the PC has a plate scale of 0.046" per pixel, the 0.5" aperture radius corresponds to 10.87 pixels.

Steps for determining aperture corrections from radius = 2 pixels to radius = 10.87 pixels:

1. A few "clean" stars in the field are needed so a careful measurements of flux in different apertures can be done. The stars should have a good signal-to-noise ratio, must not lie in areas with defective pixels, or be subjected to scattered light from nearby bright stars. Use the task *tvmark* to interactively select the stars and save their coordinates to a file.

   ```
   disp f555w.hhh 1
   tvmark 1 aper_corr.pos mark=circle radii=10 deletions=del interactive=yes
   ```

   To verify the stars, display them again.

   ```
   disp f555w.hhh 1
   tvmark 1 aper_corr.pos mark=circle radii=14
   ```

2. Figure out the aperture correction from 2 pixels to a 0.5" radius aperture. Since the PC plate scale is 0.046"/pixel, the 0.5" radius aperture corresponds to 10.87 pixels. Run photometry for aperture radius 2 pixels and 10.87 pixels (0.5") on the stars selected in step 1.

   ```
   unlearn phot
   unlearn datapars
   unlearn centerpars
   unlearn fitskypars
   ```

```
unlearn photpars

phot f555w.hhh[1] "" coords=aper_corr.pos output=temp1 aperture=2,10.87 \
salgori=ofilter  annulus=11 dannu=14 exposure=exptime readnoi=7.1 \
epadu=7 calgorithm=none interac=no verify=no
```

3. Extract some useful values from the *phot* output file and place it in a table.

```
txdump temp1 "ID,XCENTER,YCENTER,STDEV,FLUX,MAG,MERR" \
yes > temp2
```

Convert the text file temp2 to a table. A "format" table that defines each column is needed.

```
print "f5_id      i" > f555w_format
print "f5_x       r" >> f555w_format
print "f5_y       r" >> f555w_format
print "f5_stdev   r" >> f555w_format
print "f5_flux2    r"  >> f555w_format
print "f5_flux10p87    r"  >> f555w_format
print "f5_mag2    r" >> f555w_format
print "f5_mag10p87   r" >> f555w_format
print "f5_merr2   r" >> f555w_format
print "f5_merr10p87  r" >> f555w_format


tcreate f555w_pc_apercorr f555w_format temp2
```

4. Calculate the difference in magnitude between aperture=2 and aperture=10.87.

First,

```
tcalc f555w_pc_apercorr f5_mag2_10p87  "f5_mag10p87 - f5_mag2"
```

Then, get the mean of the calculated values above. That's the aperture correction from aperture=2 to aperture=10.87.

```
tstat f555w_pc_apercorr f5_mag2_10p87
```

```
# f555w_pc_apercorr  f5_mag2_10p87
# nrows          mean        stddev       median         min          max
11      -0.3758187727     0.0750728   -0.376001       -0.507     -0.207001
```

For this example, the aperture correction for stars in f555w.hhh[1] from aperture radius = 2 to aperture radius = 10.87 is -0.3758 +/- 0.0751 magnitudes

Apply this correction to the magnitudes computed in section 4.3.4.

```
tcalc f555w_pc f5_mag0p5 "(f5_mag + (-0.3758))"
```

The same is done for f814w[1] data.

Use the same star coordinate file in the previous example to determine aperture corrections for the f814w.hhh image.

Figure out the aperture correction for a 0.5" radius aperture. Since the PC plate scale is 0.046"/pixel, the 0.5" radius aperture corresponds to 10.87 pixels. Run photometry for aperture radius 2 pixels and 10.87 pixels (0.5") using the coordinates in *aper_corr.pos*.

```
unlearn phot
unlearn datapars
unlearn centerpars
unlearn fitskypars
unlearn photpars
phot f814w.hhh[1] "" coords=aper_corr.pos output=temp1 \
aperture=2,10.87 salgori=ofilter  annulus=11 exposure=exptime \
dannu=14 readnoi=7.1 epadu=7 calgorithm=none interac=no verify=no
```

Extract some useful values from the *phot* output file and place it in a table.

```
txdump temp1 "ID,XCENTER,YCENTER,STDEV,FLUX,MAG,MERR" \
yes > temp2
```

Convert the text file temp2 to a table. A "format" table that defines each column is needed.

```
print "f8_id      i" > f814w_format
print "f8_x       r" >> f814w_format
print "f8_y       r" >> f814w_format
print "f8_stdev   r" >> f814w_format
print "f8_flux2    r"  >> f814w_format
print "f8_flux10p87    r"  >> f814w_format
print "f8_mag2    r" >> f814w_format
print "f8_mag10p87   r" >> f814w_format
print "f8_merr2   r" >> f814w_format
print "f8_merr10p87  r" >> f814w_format


tcreate f814w_pc_apercorr f814w_format temp2
```

Calculate the difference in magnitude between aperture=2 and aperture=10.87.

First,

```
tcalc f814w_pc_apercorr f8_mag2_10p87  "f8_mag10p87 - f8_mag2"
```

Then, get the mean of the calculated values above. That’s the aperture correction from aperture radius = 2 to radius = 10.87.

```
tstat f814w_pc_apercorr f8_mag2_10p87
```

```
# f814w_pc_apercorr  f8_mag2_10p87
# nrows          mean       stddev       median        min          max
11    -0.5049088218   0.0830692     -0.53599      -0.577       -0.295
```

For this example, the aperture correction for stars in f814w.hhh[1] from aperture radius=2 to aperture radius 10.87 is -0.5049 +/- 0.0831 magnitude

Apply this flux correction to the magnitudes computed in section 4.3.4.

```
tcalc f814w_pc f8_mag0p5 "(f8_mag + (-0.5049))"
```

4.4.2 Computing CTE-corrected Magnitudes

One of the most important variables in the CTE equations is the background. Images with high background tend to have less CTE effects because the higher background levels fill the traps in the potential wells that would otherwise trap some of the signal while it is clocked down the columns (causing the CTE effect).

For uncrowded fields, the background value is simply the average of background measurements at several different locations on the image. However, this particular image does not have a constant background level. Scattered light from bright stars in the middle of the image cause an elevated background in the center of the image. Scattered light from other stars create local patches of elevated background. In such a situation, it’s very difficult to determine how CTE affects each star. That’s because CTE depends on the background levels of pixels in the columns above the star, not just the background surrounding the star. Unfortunately, that’s extremely difficult to do, so we will just use the mean local background of each star to estimate the CTE effect. This value is obtained from the mean sky value (msky) for that star as calculated by *phot*.

The Dolphin CTE equations (as of early May) are

```
XCTE = exp(-0.010*lbg)*(0.0259) * X/800
YCTE =
(0.246+exp(-0.445*lct))*(exp(-0.0356*bg)+0.461*exp(-0.232*lbg))*(0.0697+0.0240*yr-
0.00014*yr*yr) * Y/800
```

where,

```
yr = (MJD - 50193) / 365.25
lct = ln(counts) - 7, in electrons
lbg = ln(background) - 1, in electrons
```

We will need the epoch of the observations. First, get the Modified Julian Date from the image header file, then convert it to the SMS date using the task *epoch*. Then convert the SMS date to the decimal year format.

```
hsel f555w.hhh expstart yes
```

```
5.146495571299E+04
--> (5.146495571299E+04 - 50193) / 365.25  = 3.4824
```

Calculate 1) lct, 2) lbg, 3)Ycte, 4) Xcte, 5) Instrument Magnitude

1. The counts in electrons, in a 0.5" aperture is

   10**((zeropoint-magnitude)/2.5)*gain * exposure time (in seconds)

   ```
   tcalc f555w_pc  f5_ectr_0p5  "10**((22.461-f5_mag0p5)/2.5) * 7 * 700"
   ```

   Natural log of that value:

   ```
   tcalc f555w_pc f5_lct  "log(f5_ectr_0p5) - 7"
   ```

2. The sky background value lbg will be obtained from the total mean sky value in the annulus around each star, which was calculated by *phot* (f5_msky, in DN, in the table). Convert this value to electrons by multiplying with the gain.

   ```
   tcalc f555w_pc f5_bg "f5_msky * 7"
   tcalc f555w_pc f5_lbg "log(f5_bg) - 1"
   ```

3. Calculate *Ycte* for f555w.hhh[1]

   YCTE = (0.246+exp(-0.445*lct))*(exp(-0.0356*bg)+0.461*exp(-0.232*lbg))*(0.0697+0.0240*yr-0.00014*yr*yr) * Y/800

   ```
   tcalc f555w_pc f5_ycte \
   "(0.246+exp(-0.445*f5_lct))*(exp(-0.0356*f5_bg)+0.461*exp(-0.232*f5_lbg))*(
   0.0697+0.0240*3.4824-0.00014*3.4824*3.4824) * f5_y/800"
   ```

4. Calculate *Xcte* for f555w.hhh[1]

   XCTE = exp(-0.010*lbg)*(0.0259) * X/800

   ```
   tcalc f555w_pc f5_xcte "exp(-0.010*f5_lbg)*(0.0259) * f5_x/800"
   ```

5. The instrument magnitude is

   WFPC2 = -2.5 log (electrons/s) + ZP(FG) - CTE

   ```
   tcalc f555w_pc f5_wfpc2 "(-2.5 * log10(f5_ectr_0p5/700)) + 22.461 - (f5_ycte +
   f5_xcte)"
   ```

Similarly, for F814W data:

1. The counts in electrons, in a 0.5" aperture is

   10**((zeropoint - magnitude)/2.5) * gain * exposure time (in seconds)

   ```
   tcalc f814w_pc  f8_ectr_0p5  "10**((21.587-f8_mag0p5)/2.5) * 7 * 700"
   ```

   Natural log of that value:

   ```
   tcalc f814w_pc f8_lct  "log(f8_ectr_0p5) - 7"
   ```

2. The sky background value lbg will be obtained from the total mean sky value in the annulus around each star, which was calculated by *phot*

(f8_msky, in DN, in the table). Convert this value to electrons by multiplying with the gain.

```
tcalc f814w_pc f8_bg "f8_msky * 7"
tcalc f814w_pc f8_lbg "log(f8_bg) - 1"
```

3. Calculate *Ycte* for f814w.hhh[1]

```
tcalc f814w_pc f8_ycte \
"(0.246+exp(-0.445*f8_lct))*(exp(-0.0356*f8_bg)+0.461*exp(-0.232*f8_lbg))*(
0.0697+0.0240*3.4824-0.00014*3.4824*3.4824) * f8_y/800"
```

4. Calculate *Xcte* for f814w.hhh[1]

```
tcalc f814w_pc f8_xcte "exp(-0.010*f8_lbg)*(0.0259) * f8_x/800"
```

5. The instrument magnitude is

WFPC2 = -2.5 log (electrons/s) + ZP(FG) - CTE

```
tcalc f814w_pc f8_wfpc2 "(-2.5 * log10(f8_ectr_0p5/700)) + 21.587 - (f8_ycte +
f8_xcte)"
```

Note: When applying the CTE corrections to combined images, each of the combined images should have the same or closely similar exposure time. Determining the CTE correction for a combined image created from images with unequal exposure times (for example, one long exposure and one short exposure) cannot be easily done.

4.4.3 Contamination Corrections

Contaminants accumulate on the CCD windows over time, producing a time-dependent loss of throughput. While contamination has very little effect in the visible and near-IR wavelengths, it does impact UV observations. Therefore, the WFPC2 is warmed to about +22˚C for about 6 hours to remove the buildup of contaminants. This used to be done every 28 days. However, recent photometric monitor data has shown a decrease in the contamination rate, making it possible to safely increase the interval between decontaminations to 49 days.

Information on contamination rates can be found in Instrument Science Report 98-03: WFPC2 Long-Term Photometric Stability, by S. Baggett and S. Gonzaga, located at

http://www.stsci.edu/instruments/wfpc2/Wfpc2_isr/wfpc2_isr9803.html

These values will be updated in the near future so please keep checking the WFPC2 website.

The examples this tutorial use images taken with F555W and F814W filters, so contamination corrections are not required. But for the sake of completeness, here’s an example of how to make contamination corrections for UV observations, using UV images of the WFPC2 standard star GRW+70D5824. The columns in the table below are

Flux Measured countrate for aperture with radius = 0.5"

Flux Error of measured countrate

Chip Detector ID

Filter UV Filter used for observation

Rootname the dataset name of the observation

Exptime image exposure time

MJD Modified Julian Date

Aper Aperture radius

DSD The number of days between the observation and last-previous decontamination

Measured Flux	Measured Flux error	Chip	Filter	Rootname	Exptime	MJD	Aper	DSD
62.05832	0.2165556	3	F160BW	u6hidg01m	100.	52273.7092	5.	3.564671
165.1962	0.5964949	1	F170W	u6hidg08m	40.	52273.7259	11.	3.581338
124.8533	0.4905213	3	F218W	u6hidg02m	40.	52273.7120	5.	3.567449
155.4533	0.541315	3	F255W	u6hidg03m	40.	52273.7141	5.	3.569532
757.8792	2.165823	3	F336W	u6hidg04m	12.	52273.7161	5.	3.571615

These UV observations were taken on December 30, 2001, about 3.5 days after a decontamination on MJD 52270.14. The dates of WFPC2 decontaminations can be found at

http://www.stsci.edu/instruments/wfpc2/Wfpc2_memos/wfpc2_decon_dates.html

UV throughput rates have changed over time since WFPC2 was first installed in 1993. Throughput decline rates can be found in table 2 in ISR 98-03, divided into four epochs from 1994 to 1998. An analysis of the most recent contamination rates will be issued shortly (in the ISR, Updated Contamination Rates for WFPC2 UV Filters by McMaster et al.), so please check the WFPC2 webpage for the latest information.

For the above observations, the throughput decline rates, according to table 2 in ISR 98-03, are:

Filter	Chip	%Decline/Day	Error
F160BW	WF3	1.093	0.065
F170W	PC	0.452	0.013
F218W	WF3	0.633	0.047
F255W	WF3	0.327	0.012
F336W	WF3	0.181	0.010

Therefore, the decline in flux is

Corrected Flux = Flux * (1 + (% decline per day/100) * (Days since Decon))

Flux	Filter/chip	%Decline/Day	Days Since Decon	Corrected Flux
62.0583	F160BW/3	1.093	3.564671	64.4762
165.196	F170W/1	0.452	3.581338	167.870
124.853	F218W/3	0.633	3.567449	127.672
155.453	F255W/3	0.327	3.569532	157.267
757.879	F336W/3	0.181	3.571615	762.778

4.5 Converting from Instrument Magnitude to Standard Magnitude

First, calculate the (V - I) color for the stars.

Sort both tables by star ID.

```
tsort f555w_pc f5_id
tsort f814w_pc f8_id
```

Make a backup copy of the table, in case you later need to redo some of the steps.

```
tcopy f555w_pc f555w_pc_backup
tcopy f814w_pc f814w_pc_backup


tproject  f555w_pc f555w_temp \
columns="f5_id,f5_x,f5_y,f5_stdev,f5_merr,f5_xcte,f5_ycte,f5_ectr_0p5,f5_wfpc2"
tproject  f814w_pc f814w_temp \
columns="f8_id,f8_x,f8_y,f8_stdev,f8_merr,f8_xcte,f8_ycte,f8_ectr_0p5,f8_wfpc2"
```

Merge the two tables. But before that, change the column names *f5_id* and *f8_id* to *star_id* in each table. (Note: this is safe to do because the same star list was used for measuring both F555W and F814W, so the order of stars is identical.)

```
tchcol f555w_temp f5_id star_id "" ""
tchcol f814w_temp f8_id star_id "" ""
tmerge "f555w_temp,f814w_temp" v-i_pc_temp merge allcols=yes
```

For quality control, discard sky standard deviations greater than 10.

```
tsel v-i_pc_temp  v-i_pc "f5_stdev .le. 10 && f8_stdev .le. 10"
```

Calculate V-I colors for the stars:

```
tcalc v-i_pc v_i  "f5_wfpc2 - f8_wfpc2"
```

A color-magnitude diagram can now be plotted using your favorite plotting package. In this example, *igi* is used (*stsdas.graphics.stplot*).

Create a file called "igi_cmd.plot" containing the *igi* commands listed below. But first, determine the limits for the plot's x and y axes (color and f555w-magnitude). This is easily done using the task *tstat* to get minimum and maximum values, as well as the mean and standard deviation of the points to be plotted.

```
tstat v-i_pc v_i

# v-i_pc  v_i
#  nrows    mean            stddev      median      min         max
   1287     0.4420775326    0.286081    0.373859    -0.382202   2.25028


tstat v-i_pc f5_wfpc2

# v-i_pc  f5_wfpc2
#  nrows    mean            stddev      median      min         max
   1288     19.05196783     1.51605     19.2479     15.1116     21.7565
```

```
#<igi plot file>
print "data v-i_pc.tab# specify the data source" > igi_cmd.plot
print "xcol v_i; ycol f5_wfpc2# specify x,y columns to be plotted" >> igi_cmd.plot
print "  " >> igi_cmd.plot
print "limits -0.3 2.5 22 15 # define x,y axes limits. " >> igi_cmd.plot
print " "  >> igi_cmd.plot
print "box# specify the type of plot" >> igi_cmd.plot
print "expand 0.2# specify size of points" >> igi_cmd.plot
print "ptype 12 3# specify type of points" >> igi_cmd.plot
print "points     " >> igi_cmd.plot
print "expand 1.2# text size of x,y labels" >> igi_cmd.plot
print "ylabel F555W Magnitude                " >> igi_cmd.plot
print "xlabel F555W - F814W  " >> igi_cmd.plot
print "title Color-Magnitude Diagram for NGC2100 PC Data" >> igi_cmd.plot
#<end igi plot file>
```

To run the plot file from the IRAF command line:

```
igi < igi_cmd.plot
```

First, save the plot to a metacode file. Then use the task *psikern* to convert the metacode file to a postscript file.

```
igi < igi_cmd.plot >G cmd_ngc2100
psikern cmd_ngc2100 device=psi_defm out=cmd_ngc2100.ps
```

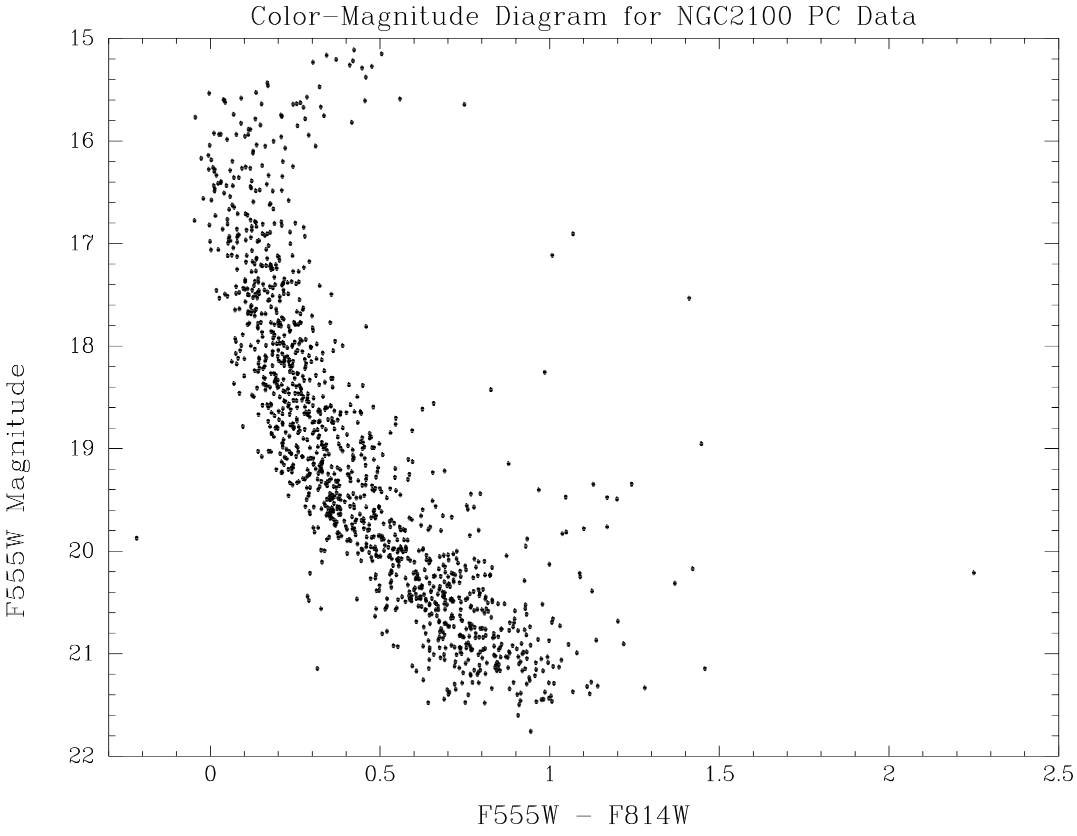
or

```
igi < igi_cmd.plot device=psi_land
```

(This second example creates a temporary file in your machine's /tmp directory. Just copy it to your working directory and rename it with a .ps extension.)

Here's what the plot looks like:

Figure 10: Figure 10: Color-Magnitude diagram of NGC2100 using stars from the PC.



Note about using transformations: Although it is possible to define a "photometric transformation" to convert the photometry results to one of the standard systems, we generally do not recommend it. These transformations have limited precision; they depend on color range, metallicity, and surface gravity of the stars. Errors of 0.2 magnitudes or more can occur, depending on the filter used and on how much the spectral energy distribution of the measured objects differs from that of the objects on which the transformation is defined. Therefore, we recommend that the WFPC2 photometric results be referred to a system based on its own filters, if possible (e.g. compare results to simulations made in the WFPC2 filters rather than UBVRI, if available).

Having said that, let's try the conversion anyway ....

The most widely-used method for transforming from a filter magnitude to the Johnson-Cousins system is using the transformation coefficients published by Jon Holtzman et al. in their paper, The Photometric Performance and Calibration of WFPC2 (a link is available at http://www.stsci.edu/instruments/wfpc2/wfpc2_doc.html#Phot). Updated zeropoints can be found in Andrew Dolphin's website at http://www.noao.edu/staff/dolphin/wfpc2_calib/. Details about how these zeropoints were derived can be found in his paper, The Charge-Transfer Efficiency and Calibration of WFPC2, Publications of the Astronomical Society of the Pacific, 112:1397-1410, 2000 October. (A link to the paper is available at Dolphin's website, mentioned above.)

The stars in these images are in NGC 2100, a star cluster in the Large Magellanic Cloud, and represent a wide range of stellar types. Calculating standard magnitudes will require at least one of the colors. The F555w - F814W colors, computed previously, will be used.

The transformation equation (taken from Dolphin's webpage, as of early May) is:

SMAG = -2.5 log (DN/s) + ZP(FS) + T1 SCOL + T2 SCOL^2 - CTE

where

DN/s = measured countrate in electrons

ZP(FS) = flight system zeropoint for the filter/chip (available at Dolphin's webpage)

SCOL = color (F555W - F814W) computed in earlier section

T1, T2 = transformation coefficients (available at Dolphin's webpage)

CTE = CTE of each star, computed in the previous section

Calculate Johnson V magnitudes in a 0.5" radius aperture:

```
tcalc v-i_pc v_0p5 \
"-2.5 * log10(f5_ectr_0p5/700) + 22.461 + (-0.052*v_i) + (0.027*v_i*v_i) - (f5_xcte+f5_ycte)"
```

Calculate Cousins I magnitudes in a 0.5" radius aperture:

```
tcalc v-i_pc i_0p5 \
"-2.5 * log10(f8_ectr_0p5/700) + 21.587 + (-0.062*v_i) + (0.025*v_i*v_i) -
(f8_xcte+f8_ycte)"
```

One last correction needs to be made to the magnitudes. The current magnitudes are for a 0.5" aperture radius. A correction to an infinite aperture is defined as simply subtracting 0.1 magnitudes from that value.

For Johnson V & Cousins I magnitudes for an infinite aperture:

```
tcalc v-i_pc v_mag "v_0p5 - 0.1"
tcalc v-i_pc i_mag "i_0p5 - 0.1"
```

It’s generally difficult to keep track of all the systematic errors that accumulate in the course of photometry reductions. A common approach is to include an estimate of the systematic errors in quadrature with the error estimate that comes out of *phot*. In the example below, these systematic errors are:

1. 0.02 magnitudes. This error is based on the scatter between various authors’ zeropoint determinations for the major broadband filters. (This value was provided by Brad Whitmore, based on his analysis of other published WFPC2 zeropoints in the literature.)
2. 25% of total CTE. An error estimate of 25% in the uncertainty for CTE, based on a comparison between the Whitmore et al. formula and the Dolphin formula.

Therefore, the overall error estimate for a given magnitude value is:

$$\sqrt{(\text{phot magnitude error})^2 + 0.02^2 + (\text{CTE error estimate})^2}$$

```
tcalc v-i_pc v_mag_err \
  "sqrt((f5_merr**2) + 0.02**2 + (((f5_xcte+f5_ycte)*0.25)**2))"
tcalc v-i_pc i_mag_err \
  "sqrt((f8_merr**2) + 0.02**2 + (((f8_xcte+f8_ycte)*0.25)**2))"
```

References

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