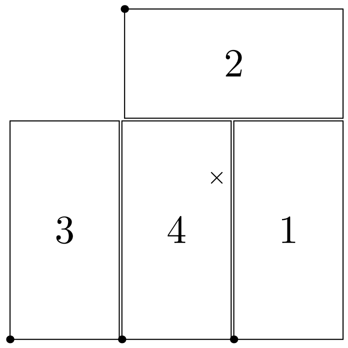
1 Astrometric calibration for INT Wide Field Camera images

The Wide Field Camera instrument on the Isaac Newton Telescope contains four CCD chips of 2048×4096 pixels positioned roughly, but not exactly, as follows:



In order to do accurate astrometry with data obtained from this instrument, it is necessary to correct for the exact orientation and position of each CCD in relation to the others, as well as for nonlinear distortions away from the optical axis of the focal plane introduced by the optics of the telescope. The nonlinear distortion is very well modelled by a radial "pincushion" transformation, which has the form

$$r' = r(1 + Dr^2)$$

The following transformations take account of both these effects to map the pixel coordinates (x_i, y_i) of CCD$\#i$ into a new pixel-like coordinate system (x', y') of uniform scale, which is the same for all four CCDs. The origin of this coordinate system is at pixel coordinates $(1778, 3029)$ of CCD#4, which is taken to be on the optical axis. At this point, one unit of the new coordinate system is equivalent to one pixel of the CCD#4 system, so that the new coordinates are almost equivalent to CCD#4 coordinates, although they diverge away from the origin thanks to the nonlinear distortion. Each unit of the new coordinates has the same size, which is approximately 0.333 arcsec.

The corrected coordinates (x', y') are obtained from each set of pixel coordinates (x_i, y_i) by first translating so that the origin is on the optical axis, then rotating to the correct angle, then correcting for the radial distortion effect:

$$\begin{aligned}
x_i^{\text{shift}} &= x_i - X_i \\
y_i^{\text{shift}} &= y_i - Y_i \\
x_i^{\text{rot}} &= x_i^{\text{shift}} \cos\theta_i - y_i^{\text{shift}} \sin\theta_i \\
y_i^{\text{rot}} &= x_i^{\text{shift}} \sin\theta_i + y_i^{\text{shift}} \cos\theta_i \\
x' &= x_i^{\text{rot}} \left(1 + D\left[x_i^{\text{rot}\,2} + y_i^{\text{rot}\,2}\right]\right) \\
y' &= y_i^{\text{rot}} \left(1 + D\left[x_i^{\text{rot}\,2} + y_i^{\text{rot}\,2}\right]\right)
\end{aligned}$$

Where (X_i, Y_i) are the coordinates of the optical centre of the instrument in the pixel coordinate system of CCD$\#i$, θ_i is the angle at which CCD$\#i$ sits on the focal plane, and D is the pincushion distortion coefficient.

Values for these coefficients have been obtained by registering two exposures of the same region of sky, in which the instrument had been rotated by 180° between exposures. The value of (X_4, Y_4) was taken from the value used for the Wide Field Survey data, and θ_4 was chosen to be zero. The values of the coefficients in these equations are approximately:

$$\begin{array}{llllll}
X_1 = & -336.74 & Y_1 = & 3039.14 & \theta_1 = & 0.01868^\circ \\
X_2 = & 3180.68 & Y_2 = & 1729.67 & \theta_2 = & -90.62115^\circ \\
X_3 = & 3876.73 & Y_3 = & 2996.30 & \theta_3 = & 0.11436^\circ \\
X_4 = & 1778.00 & Y_4 = & 3029.00 & \theta_4 = & 0.00000^\circ
\end{array}$$

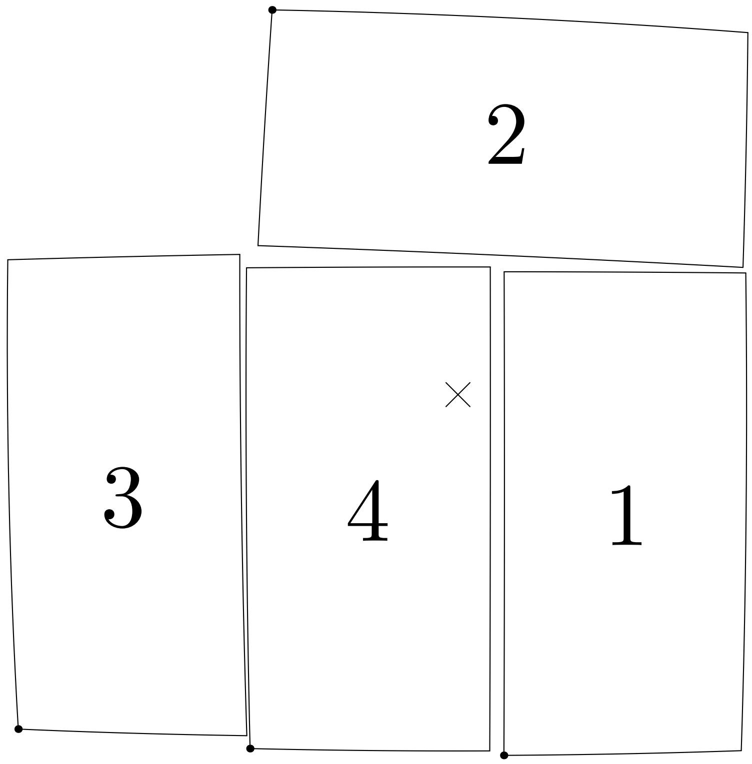
and

$$D = -5.30 \times 10^{-10} \mathrm{pixel}^{-2}$$

This value of D corresponds in units of radians to $-203\,\mathrm{rad}^{-2}$, compared to the value $-259.8\,\mathrm{rad}^{-2}$ quoted in the ING observer handbook.

These values of the coefficients are thought to be correct to an accuracy of 1 or 2 pixels, which is around half an arcsecond.

The following image gives an exaggerated representation of the shapes and positions of the CCDs as mapped on to the new coordinate system. The dots in the corners of the CCDs mark the pixel origin for each CCD and the "×" marks the origin of the unified coordinate system.



2 Attaching modified coordinates using CCDPACK

For users of Starlink software, the calibrated coordinate information can be attached automatically to image files using the ASTIMP command, and the file `INT-WFC.ast`[1]

There are a couple of provisos for using this facility: first, it is best if the files are converted to Starlink NDF format using the CONVERT package as follows:

```
% convert

   CONVERT commands are now available -- (Version 1.2-4, 2000 January)

   Defaults for automatic NDF conversion are set.

   Type conhelp for help on CONVERT commands.
   Type "showme sun55" to browse the hypertext documentation.

% fits2ndf in='r10628?.fits' out='*'
```

which will convert the FITS file `r106280.fits` into the NDF `r106280.sdf` and so on. The Starlink software will in fact work with FITS files, but because it converts them on the fly between FITS and NDF formats before and after each command, this can be rather slow with files the size of WFC frames.

Secondly, you must have CCDPACK version 3. This will be in the Starlink Spring 2000 release, which at the time of writing this document has not been distributed. However, copies can be obtained on request from Mark Taylor at `mbt@ast.cam.ac.uk`.

Once the file is in Starlink NDF format, then obtain the file `INT-WFC.ast` and from the Unix C shell do the following:

```
% ccdpack

   CCDPACK commands are now available -- (Version 3.0-1)

  For help use the commands ccdhelp or ccdwww

% astimp in='r10628?' astfile=INT-WFC.ast reset accept

    ASTIMP
    ======
  Framesets read from file INT-WFC.ast:
    FITS header "ROTSKYPA" used for rotation

     N    Base domain        Current domain      Frameset ID
     --   -----------        --------------      -----------
     1    PIXEL              INT-WFC             FITSID CHIPNAME 'A5506-4'
     2    PIXEL              INT-WFC             FITSID CHIPNAME 'A5383-17-7'
     3    PIXEL              INT-WFC             FITSID CHIPNAME 'A5530-3'
     4    PIXEL              INT-WFC             FITSID CHIPNAME 'A5382-1-7'
  4 NDFs accessed using parameter IN
```

[1] ftp://capc23.ast.cam.ac.uk/pub/star/register/INT-WFC.ast

```
Processing NDF /data/cass58a/mbt/data/int4/r106280
  Matched with frameset ID "FITSID CHIPNAME 'A5506-4'"
  Rotating additional 180 degrees
  New frame in domain "INT-WFC" added

Processing NDF /data/cass58a/mbt/data/int4/r106281
  Matched with frameset ID "FITSID CHIPNAME 'A5383-17-7'"
  Rotating additional 180 degrees
  New frame in domain "INT-WFC" added

Processing NDF /data/cass58a/mbt/data/int4/r106282
  Matched with frameset ID "FITSID CHIPNAME 'A5530-3'"
  Rotating additional 180 degrees
  New frame in domain "INT-WFC" added

Processing NDF /data/cass58a/mbt/data/int4/r106283
  Matched with frameset ID "FITSID CHIPNAME 'A5382-1-7'"
  Rotating additional 180 degrees
  New frame in domain "INT-WFC" added
```

This command sets the Current coordinate frame of the specified NDF files to the new coordinate system (x', y') described above. As well as applying the linear and nonlinear geometry terms whose coefficients were given, it also rotates the coordinates according to the value of the ROT-SKYPA FITS header card, which records the orientation of the turntable when the observation was made; in this case it was oriented at 180°. In this way, applying the `INT-WFC.ast` file to any set of image NDF files will result in them sharing coordinates which are related by a simple shift in X and Y coordinates, since the nonlinear optical distortions, the exact positioning of the CCDs on the turntable, and the orientation of the turntable itself will have been accounted for.

Once the new coordinate system has been attached to the images, then most Starlink applications will make use of this as appropriate. If you display any of the images using KAPPA's DISPLAY application, the axes will show the coordinates in the new frame:

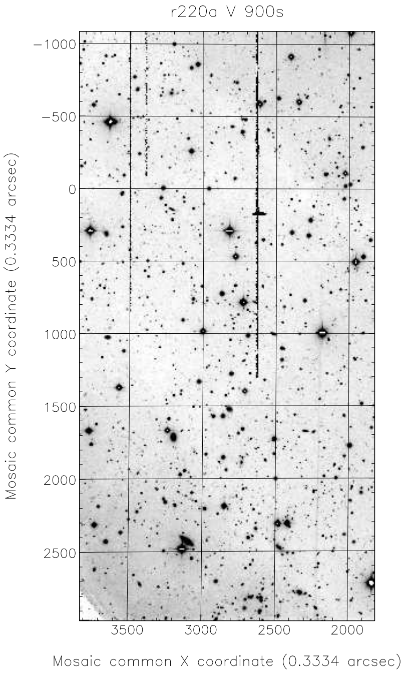
```
% kappa

   KAPPA commands are now available -- (Version 0.13-7)

   Type kaphelp for help on KAPPA commands
   Type "showme sun95" to browse the hypertext documentation

% display r106282 style='"grid=1,gap=500"'
```

will give the following display:



Close inspection will show that the grid is not quite parallel to the sides of the image, or straight, because of the slight rotation from the vertical and nonlinear distortion.

If some of the frames overlap, the corresponding X and Y offsets can then easily be determined using CCDPACK's object matching registration facilities.

Acknowledgements

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Starlink
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