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Summary

This document summarizes the coordinate transformations described in SC2/SOF/IC210/01, the applications of the transformations to the ADDWCS module, and a description of additional flips and rotations unique to the FTS-2. Appendix 1 describes the polynomial correction for FTS-2.

References

“FTS-2 Optical Design”, B.G. Gom, (SC2/FTS/OPT/001)

“FTS-2 Port Optical Coordinates”, B. G. Gom, (SC2/FTS/OPT/002)

“FTS-2 Input Port Rotation”, B.G.Gom, (SC2/FTS/OPT/003)

“SCUBA-2 Pixel Naming and Coordinate Transformations”, B. D. Kelly, (SC2/SOF/IC210/01)

Leclerc, M.R., Gom, B.G., and **Naylor, D.A.**, Optical Design of the SCUBA-2 IFTS. *Proc. SPIE, Space Telescopes and Instrumentation: Optical, Infrared, and Millimeter 7014*, (2008).

Starlink ViewVC Subversion Repository. 30 January 2009. JAC Starlink Software Collection. 22 June 2009 <<https://starlink.jach.hawaii.edu/viewvc>>

Warrant-Smith, R.F., D.S. Berry. AST - A Library for Handling World Coordinate Systems in Astronomy. 14 January 2009. Council for the Central Laboratory of the Research Councils. 22 June 2009 <<http://www.starlink.ac.uk/~dsb/ast/sun211.htx/sun211.html#stardoccontents>>

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1. Introduction

The SCUBA-2 FTS, designed for use at the JCMT, is mounted at the exit of the telescope's elevation bearing at left Nasmyth. Reflecting optics relay light from telescope receiver cabin to the SCUBA-2 arrays, as seen in Figure 1. Reimaging and reflections of the light cause reversals and rotations of image before it reaches the arrays. These transformations, combined with the transformation from the recorded image to astronomical coordinates, are to be determined and attached as header information to the data files written for each subarray. Presented is a description of the transformations from the arrays to the sky with particular emphasis on the light that passes through the dual FTS-2 ports.

Following the light's path backwards from GRID to Sky, there are 4 image planes we are interested in: The final focus on one of the two SCUBA-2 subarrays, the FTS-2 Output, the FTS-2 Input/ Horizontal Bearing, and the Sky.

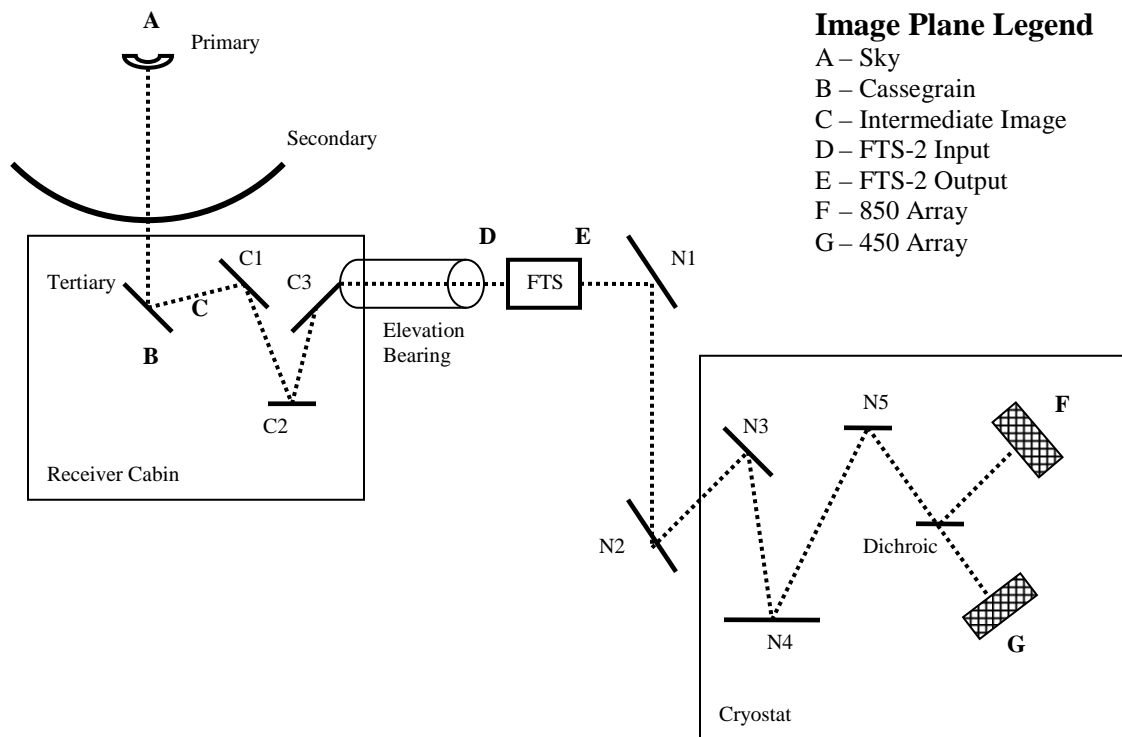


Figure 1 – A schematic of the JCMT's optics. Labels A through G indicate the location of image planes relevant to this document.

2. Software

2.1. Transformations Using AST

One of the uses of the Astronomical (AST) Library is to provide facilities for attaching world coordinate systems to astronomical data. A brief list of terminology used in this document is given below.

Frame	An Object that represents a coordinate system
SkyFrame	A type of Frame that describes celestial lon/lat coordinate systems, determined by setting a System attribute to it (for example, AzEl).
Mapping	An Object that contains the relationship between coordinate systems
FrameSet	An Object that represents a network of interrelated coordinate systems formed by connecting Mappings and Frames
ZoomMap	A type of Mapping that performs a "zoom" transformation by multiplying all coordinate values by the same scale factor
ShiftMap	A linear Mapping which shifts each axis by a specified constant value
MatrixMap	A type of Mapping that performs a general linear transformation
PolyMap	A type of Mapping that performs a general polynomial transformation
astCmpMap	This function creates a CmpMap, which is compound Mapping that allows two component Mappings (of any class) to be connected together to form a more complex Mapping.
astSimplify	This function simplifies a Mapping (which may be a compound Mapping such as a CmpMap) to eliminate redundant computational steps, or to merge separate steps which can be performed more efficiently in a single operation.

2.2. Adding a World Coordinate System

ADDWCS is a data reduction module implemented as a SMURF routine (starlink/applications/smurf/libsc2fts/sc2fts_addwcs.c). Its purpose is to add world coordinate system information for a spectral cube. This includes a 2D FrameSet created by sc2ast_createwcs and a 1D FrameSet that contains spectral information. The data format is Starlink NDF and the transformations are done by Starlink AST.

The ADDWCS module calls sc2ast_createwcs (a wrapper for sc2ast_createwcs2), which is a function defined in starlink/applications/smurf/sc2da/sc2ast.c. sc2ast.c has undergone

many modifications since it was first written. As such, coordinate transformations included in it deviate from the coordinate transformations explained in SC2/SOF/IC210/01. The following describes how those coordinate transformations are currently applied in `sc2ast_createwcs2`. The general method is to build an AST FrameSet that contains the mapping from the GRID coordinates of the bolometers to celestial coordinates, which are AzEl.

3. SCUBA-2 Focal Planes

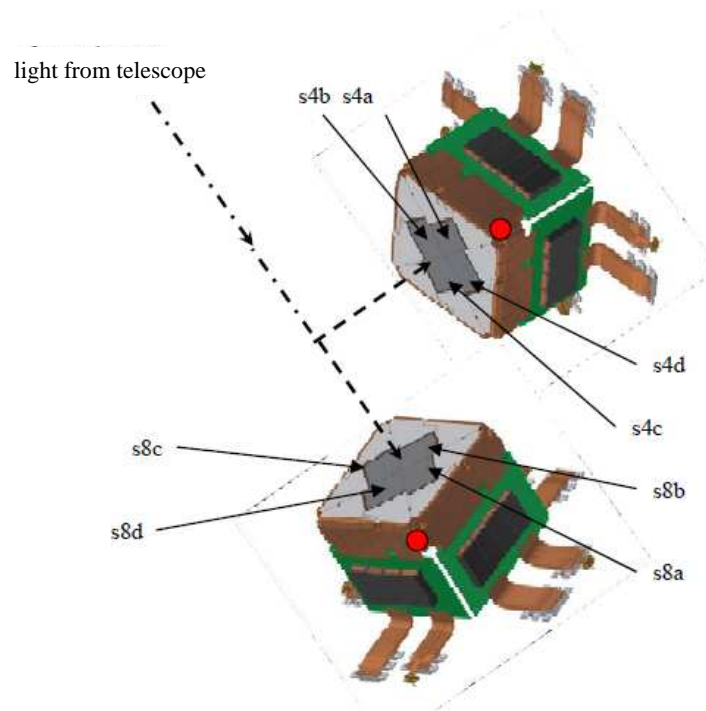


Figure 2 – The two SCUBA-2 focal plane units and subarray labelling. The units are structurally identical. The thermal key is indicated by a red dot. This image coincides with the image planes G and F in Figure1.

SCUBA-2 has two focal planes. Both units are identical apart from wavelength sensitivity, which are 850 and 450 microns. A dichroic transmits the 850 band and reflects the 450 band. Each focal plane is composed of 4 subarrays that are labelled “a” through “d” and have 32x40 bolometers. The mechanical support has a thermal contact, adjacent to one corner of the unit; this corner is identified with the “thermal key” tag, and is used for determining the orientation of the arrays. The thermal key is located on the corner between subarrays “a” and “d”.

4. GRID to Frame850/ Frame450 Coordinates

Each subarray has its own GRID coordinate system that are oriented uniquely. GRID coordinates $[i, j]$ are defined as the pixel positions for each bolometer in a given subarray. The origin for each system is at $[0, 0]$, and bolometer numbering starts at $[1, 1]$.

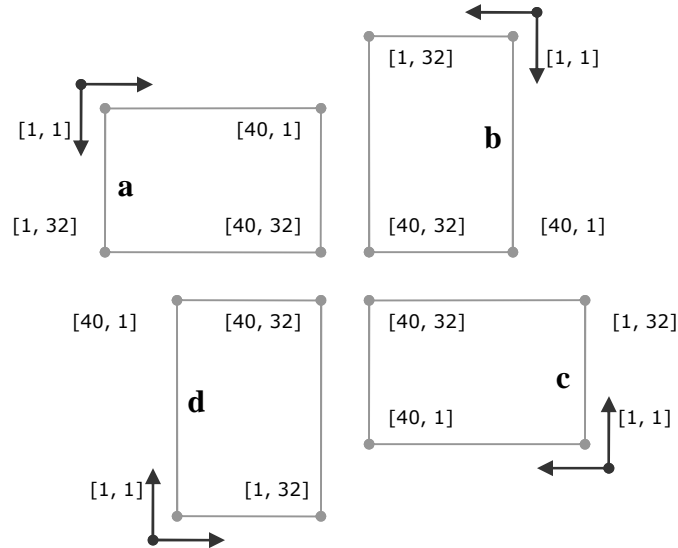


Figure 3 – SCUBA-2 subarray layout for both the 850 and 450 micron arrays as seen from behind (light coming out of the page). Sample GRID coordinates are shown.

Frame850/ Frame450 are a common Cartesian coordinate system for all the subarrays on a given array. The origin is located at the center of the array (the SCUBA-2's optical axis) and units are in millimetres. Their axis are orientated such that when the image on either array is projected to the elevation bearing (light coming out of the page) the x and y axes are pointing right and up, regardless of the azimuth or elevation of the telescope.

All four subarrays on each array have their individual GRID coordinates that are transformed into Frame850/ Frame450; each subarray's GRID coordinates will undergo their own transformations as they are uniquely orientated. The following transformations are used to calculate the position of each pixel in (Right, UP) coordinates given their $[i, j]$ pixel indices. All examples and diagrams use the s8b subarray.

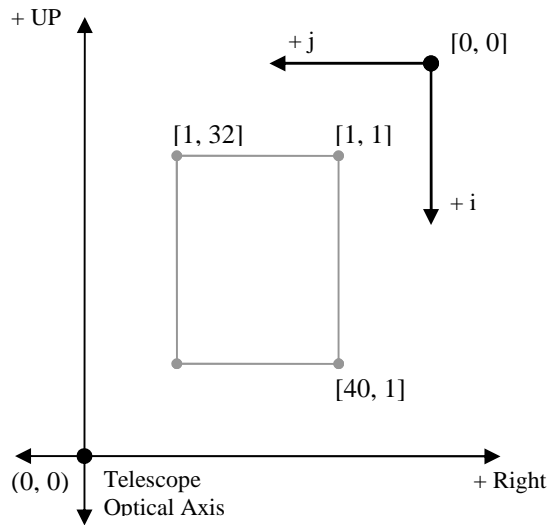


Figure 4 – A section of Frame850 coordinates showing subarray s8b. GRID coordinates are indicated by [i, j].

4.1. Z-Shift

GRID coordinates are first shifted so that the location of the origin is at the [1, 1] bolometer. A ShiftMap is used to subtract 1 from all pixel values.

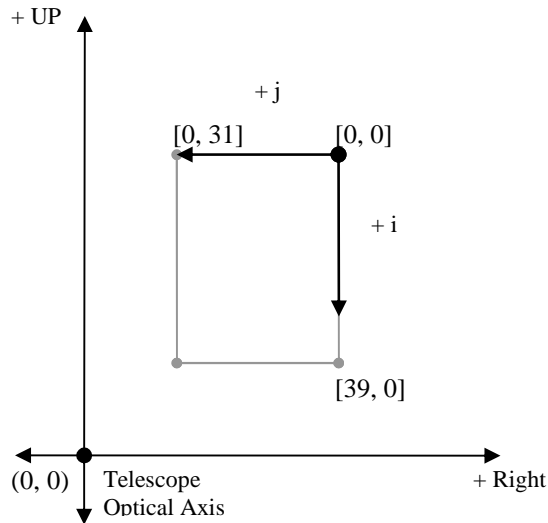


Figure 5 – Z-shift the origin of GRID coordinates to [0, 0].

4.2. Rotation Angle

Each positive “i-axis” in GRID coordinates is tilted relative to positive Frame850 “Right” by a multiple of 90°. The GRID frame is rotated to align these two axes. This transformation uses a MatrixMap.

The rotation matrix for the 850 sub-array: $\begin{bmatrix} \cos(r) & -\sin(r) \\ \sin(r) & \cos(r) \end{bmatrix}$, where $r = \pi/2$.

This produces the rotation: $i' = -j$
 $j' = i$

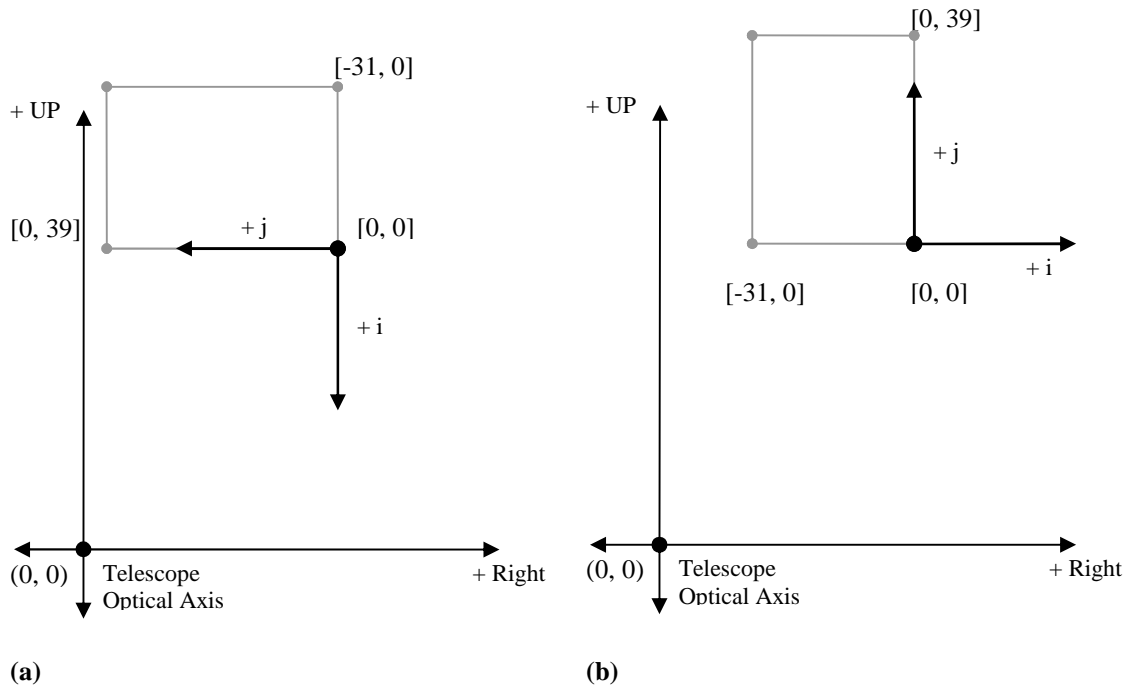


Figure 6 – (a) 90 degree rotation of GRID positions about [0, 0]. (b) GRID axes are redrawn to be right handed, that is, [i, j] corresponds to right handed (x, y).

For example, a pixel at [4, 2] would have its new position at [-2, 4]. This is equal to a 90° CW rotation. GRID coordinates are redrawn to become right-handed.

4.3. Reverse Y-Coordinate

The y-coordinate is now reversed in preparation for the next step. This transformation uses the transformation matrix $\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$. A MatrixMap is used for this transformation.

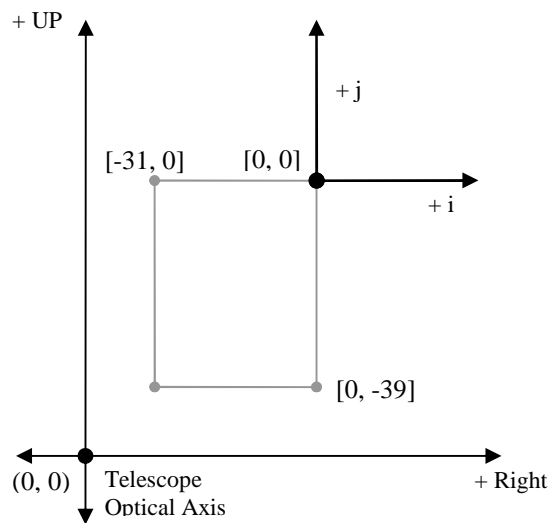


Figure 7. Flipping the GRID image over the positive i-axis.

4.4. Off-Shift

This distance from the telescope's optical axis to the [1, 1] bolometer in Figure 3 are provided for each subarray. For the s8b subarray these distances are:

xoff = 33.5 pixels

yoff = 41.5 pixels

These values are added to all [i, j] coordinates in the GRID frame, i.e. [i, j] + [xoff, yoff]. This is achieved using a ShiftMap.

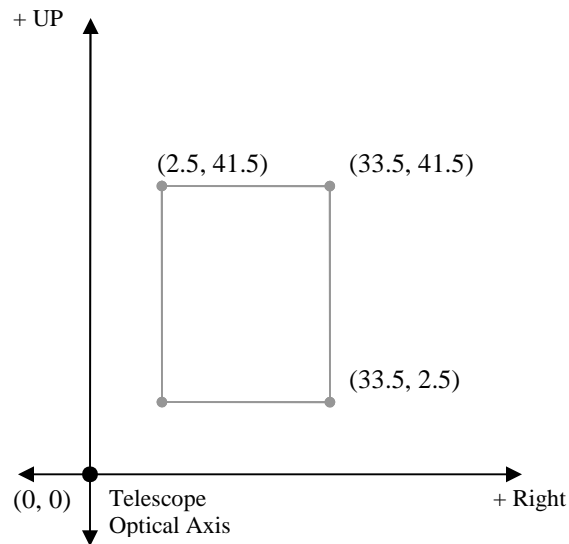


Figure 8: Off-shift: Shifting GRID coordinates into Frame850 coordinates.

4.5. Dichroic Flip

The Frame850 and Frame450 focus differ from each other only by a vertical flip. Initially, the final step into (Right, UP) coordinates was to invert the y-values for only the 450 micron array. A change (revision 28242, Fri Oct 17 00:56:55 2008, by echapin) was made that flips the 850 subarrays instead, leaving the 450 subarrays in their original orientation.

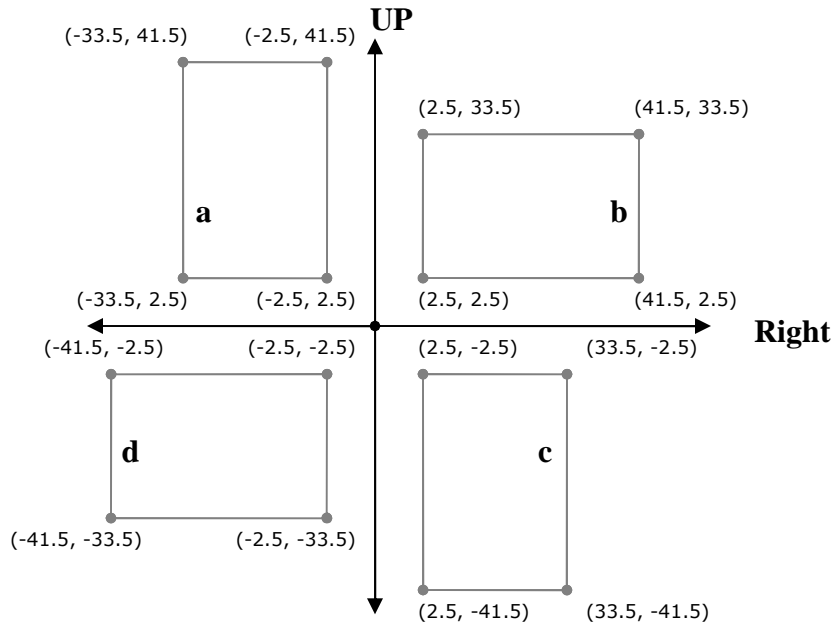


Figure 9 – Pixel positions from the individual GRID coordinate systems, as seen in Figure 3, have been transformed to fit on a common coordinate system, called Frame850. Note that units here are in pixels and should be converted to millimetres before transforming to Nasmyth coordinates.

Due to an odd number of mirrors within the cryostat, the image that reaches the 850 micron array is upside down, as it is transmitted through the dichroic. The image that reaches the 450 micro array is right side up, as it is reflected by the dichroic. Therefore, the transformation to Frame850 coordinates has an additional inverse of y-coordinates to properly align the y-values of the image with UP.

4.6. Pixels to Millimetres

A ZoomMap is used to convert pixel units to millimetres. Since pixel separation is the same in both the North and UP directions, a simple scaling of 1.135 mm/pixel is used.

4.7. Simplification

The coordinate transformation code from the SCUBA-2 project has simplified the above steps (revision 28435, Thu Nov 20 23:04:24 2008, by timj) by using two separate rotation matrices for the 850 and 450 subarrays as well as using a negative y-off value. Below are two sample calculations using s8b showing that the two methods are equivalent.

Original Code (revision 28242):	
Coordinate	Transformation
[4, 2]	GRID [i, j]
[3,1]	Z-shift
[-1, 3]	Rotation Angle
[-1, -3]	Reverse Y-Coordinate
(32.5, 38.5)	Off-shift (North, UP)
(32.5, -38.5)	Dichroic Flip

Current Code (revision 28858):	
Coordinate	Transformation
[4, 2]	GRID [i, j]
[3,1]	Z-shift
[-1, 3]	Rotation Angle
(32.5, -38.5)	Off-shift (North, UP)

A program using the AST library was written using both sequences of transformations to verify that they produce the same results (Z:\Heggie\programs\wcs_testoutput\portCalc.c and Z:\Heggie\programs\wcs_testoutput\portTrans.c). A short IDL program was also written to visualize these transformations (X:\Heggie\workspace\Default\fts2_fitting\heggie_draw850.pro).

5. Nasmyth Coordinates

Nasmyth coordinates have the same origin as Frame850 at the center of the SCUBA-2's field of view, the same approximate orientation, and units in millimetres.

Field distortion relates Nasmyth to Frame850 coordinates and is provided as a set of points ray-traced by Tully Peacocke, fitted with polynomials using least-square fitting.

5.1. Distortion Mapping

Let “x” and “y” be undistorted “field” coordinates and let “X_d” and “Y_d” be points in the distorted “real” image that is projected onto the subarrays. The polynomials that relate these coordinate systems for SCUBA-2 are provided by the ATC.

The forward transformation is defined as going from distorted (X_d, Y_d) Frame850/Frame450 coordinates to undistorted (x, y) Nasmyth coordinates (see SCUBA-2 Coordinate Systems):

$$x = 0.30037 + 0.99216 * X_d - 1.4428e-4 * X_d^2 - 3.612e-6 * X_d^3 + 9.6e-4 * Y_d - 8.628e-6 * Y_d^2 - 2.986e-7 * Y_d^3$$

$$y = 0.6518 + 1.0488e-3 * X_d - 6.58e-5 * X_d^2 - 1.63e-7 * X_d^3 + 0.98645 * Y_d - 2.218e-4 * Y_d^2 - 1.082e-6 * Y_d^3$$

The inverse transformation is defined as going from undistorted (x, y) Nasmyth coordinates to distorted (X_d, Y_d) Frame850/Frame450 coordinates.

$$X_d = -0.30461 + 1.0079 * x + 1.502e-4 * x^2 + 3.757e-6 * x^3 - 9.73e-4 * y + 9.79e-6 * y^2 + 3.135e-7 * y^3$$

$$Y_d = -0.662328 - 1.082e-3 * x + 6.956e-5 * x^2 + 1.676e-7 * x^3 + 1.0135 * y + 2.321e-4 * y^2 + 1.221e-6 * y^3$$

To correct for polynomial distortion using a PolyMap, both the forward and inverse coefficients are required.

5.2. Placement in Code

The 2D polynomial to correct the distortion is placed directly after the transformation from GRID to Frame850 coordinates. It includes all distortions due to the optical system, excluding the FTS.

5.3. Millimetres to Radians

A ZoomMap is then used to convert from millimetres to radians by using an effective plate scale of $2.4945e-5$ rad/mm (further reduced by 8% after testing).

5.4. Additional Transformations

An additional transformation not mentioned in SC2/SOF/IC210/01 but implemented in the sc2ast.c corrects for the offset of the subarray from the focal plane. This uses a ShiftMap. The values for this transformation come from header information, which is passed in as a parameter. All of the mappings up until this point, that is, from GRID to Nasmyth, are simplified using astSimplify, to merge steps and remove redundancies.

6. FTS-2 Optics

The transformations from GRID to Frame850 coordinates with the added polynomial distortion provide a well defined tangent plane coordinate system that is related to the placement of SCUBA-2 at the East (left) end of the elevation bearing. We now turn our attention to the two FTS input and output ports and how the output image will fall on the SCUBA-2 subarrays. The orientation of the FTS ports relative to the SCUBA-2 arrays is static, and thus can be used to help describe how the two SCUBA-2 focal planes, Frame850/ Frame450, will map onto the telescope's field of view.

6.1. Input and Output Port Definition

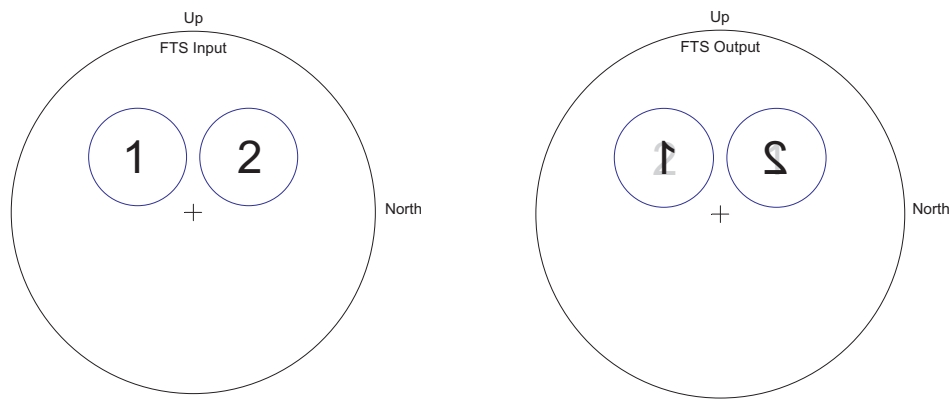


Figure 10 – (a) The FTS-2 ports at the input image plane (outside of the elevation bearing), light coming out of the page. (b) The FTS-2 output port image, produced just beyond the input image plane. Light grey numbers represent the superposition of both input ports.

Figure 10(a) shows the image produced at the elevation bearing. The upper two quadrants of this image are used for the input ports of the FTS. We define input port 1 as the port on the upper left of the image and input port 2 as the port on the upper right. The output port images are reproduced just beyond the input image plane. The presence of an interferometric difference, represented as light grey numbers in Figure 10(b), creates the need to provide specific definitions of the output ports

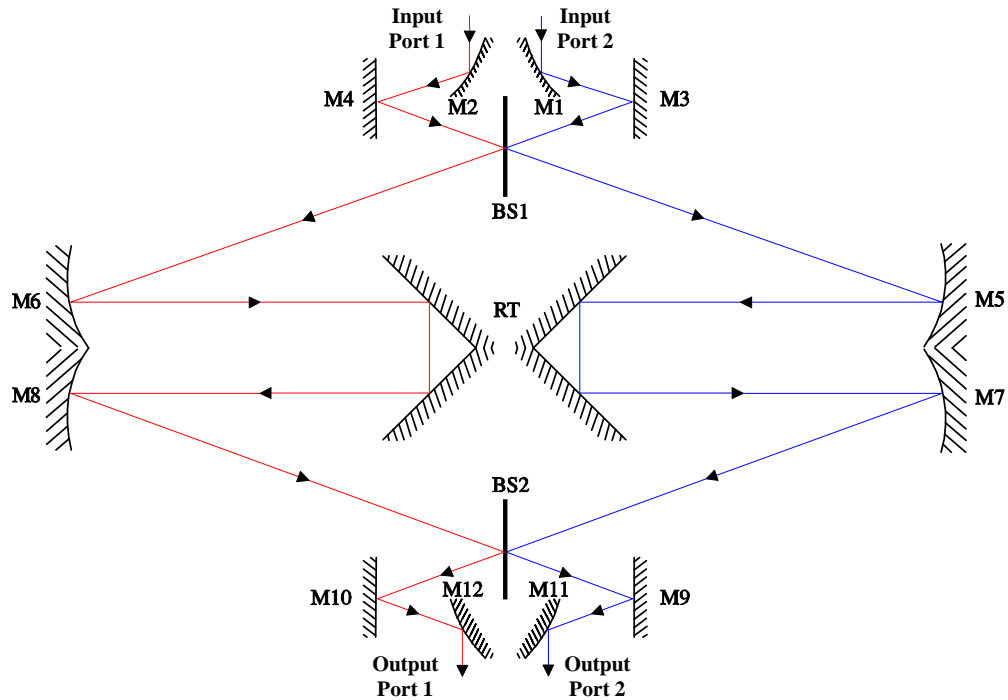


Figure 11 – A top-down view of the FTS-2 optics. The red and blue lines represent the light that leaves output ports 1 and 2 respectively.

Output port 1 is defined as the port that light leaves after passing through input port 1 and reflecting off of both beam splitters. Output port 2 is defined as the port that light leaves after passing through input port 2 and reflecting off of both beam splitters.

6.2. FTS Transformations

Due to the presence of the dichroic, the image that reaches the 850 subarrays is flipped over the horizontal axis with respects to the image leaving the horizontal bearing, causing port 1 to fall on s8d and port 2 to fall on s8c. The image reaching the 450 subarrays are not inverted, and thus port 1 falls on s4a and port 2 falls on s4b.

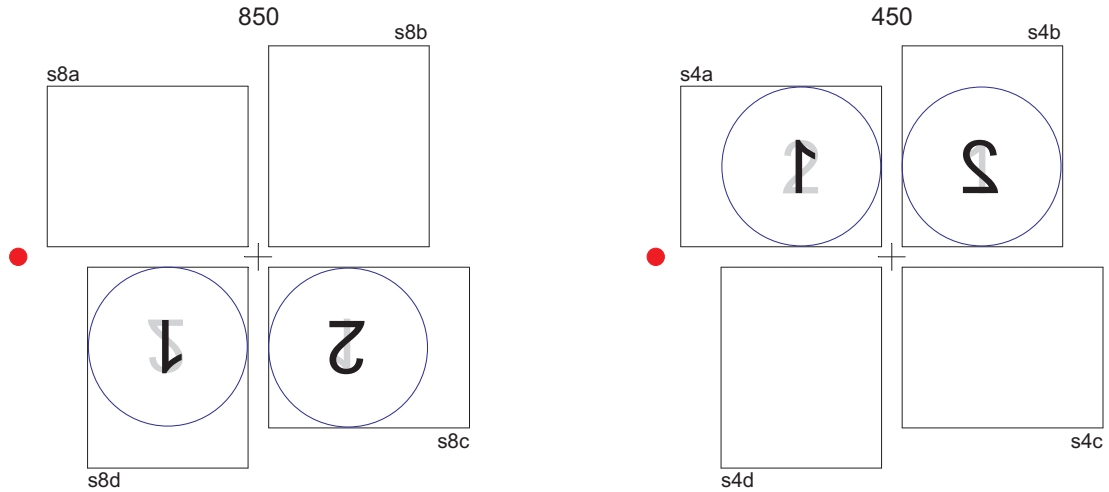


Figure 12 – The FTS-2 output images mapping onto the SCUBA-2 subarrays.

The two FTS output ports each represent the difference of the two input ports. As a result, the image on each subarray is identical (except that the interferograms are complimentary) but flipped about the vertical telescope optical axis. There is also horizontal mirroring of each output port image about the port centres due to the parity of the mirror reflections inside the interferometer.

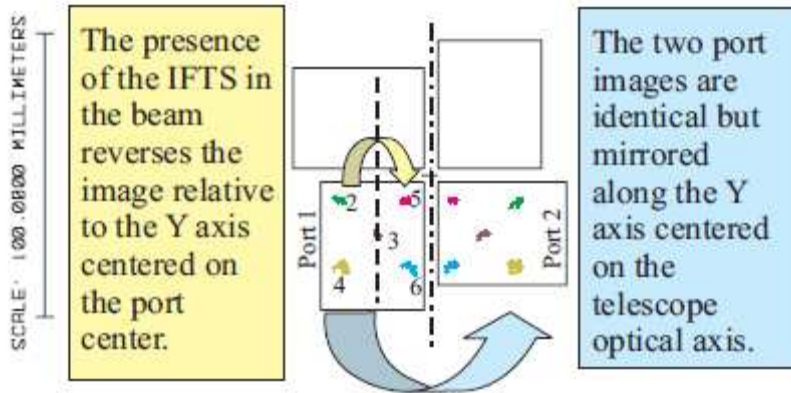


Figure 13 – The image transformations due to the FTS-2. The image in the output port (see port definitions) is flipped horizontally about the port center. The complementary image projected in port 2 is identical, but flipped horizontally over the y-axis centered on the telescope optical axis.

The FTS-2 output images fall on the two SCUBA-2 subarrays, as in Figure 12, and have their coordinates transformed from GRID pixel numbering on the individual arrays into Frame850/ Frame450 coordinates, where the x-axis points Right and the y-axis points UP when deprojected to the elevation bearing. This necessitates that the image coordinates on the 850 micron array are flipped over the x-axis, as the image is upside down due to an odd number of reflections in the cryostat. The final Frame850 and Frame450 coordinates of the ports are shown in Figure 14.

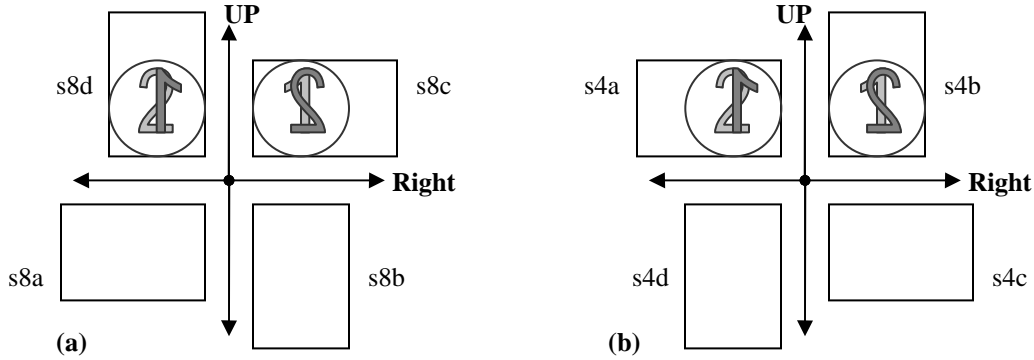


Figure 14 – Ports 1 and 2 in (a) Frame850 coordinates and (b) Frame450 coordinates. Interferometric differences are shown in light grey.

Figure 15(b) shows the orientation of the final image in the horizontal bearing when projected onto the sky.

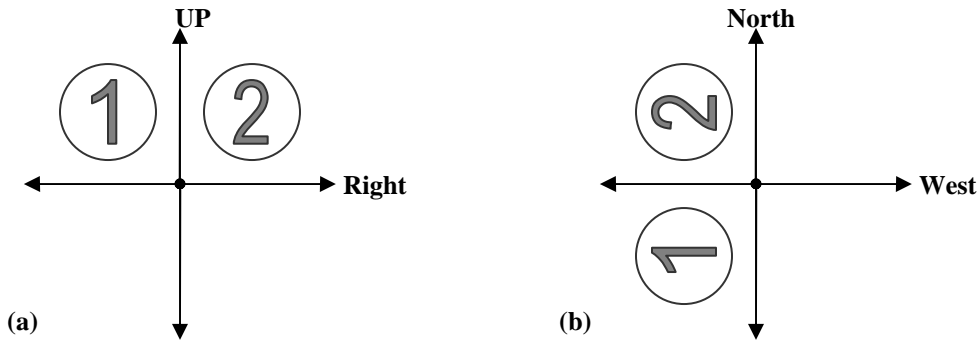


Figure 15 – (a) Nasmyth coordinates; the ideal grid of points as seen looking into the elevation bearing at the FTS-2 input image plane. (b) The same grid of points as seen through the telescope (light coming out of the page) when pointed at zenith and the elevation bearing is aligned east-west.

The final sequence of FTS-2 image transformations will apply only to subarrays s8c, s8d, s4a, and s4b, and will consist of polynomial distortion correction for the optical system that includes the SCUBA-2 and FTS-2 optics, as well as the horizontal mirroring of the image over an axis through the port's center.

7. Appendix 1: FTS-2 Polynomial Correction

This appendix describes the algorithm that applies World Coordinate System transformations that occur due to the presence of FTS-2 in the SCUBA-2 beam.

7.1. Port Coordinates

Using the radius and center of the FTS-2 ports defined in SC2/FTS/OPT/002, the following equations for each port can be derived (units are mm):

Port 1

$$(x + 20.43)^2 + (y - 20.43)^2 = 18.13^2$$

Port 2

$$(x - 20.43)^2 + (y - 20.43)^2 = 18.13^2$$

These equations were used to restrict the domain and range of the given data. Polynomials were generated within this FOV and then subsequently used to correct the distorted grid of points over the entire subarray. Fitting over the entire subarray was not possible since the distortion map is undefined for rays outside the FOV.

7.2. Fitting

Data was provided that included the ideal field coordinates in degrees and the distorted real coordinates in mm with the FTS-2 in the JCMT optical train. Zemax Configuration 3 showed light entering port 2 of the FTS-2 input; Configuration 6 corresponded to port 1.

Assuming that light from port 1 should land on s8d and light from port 2 should land on s8c, the real and ideal data are given in (Right, Down) coordinates (see FTS-2 Image Transformations or SCUBA-2 Coordinate Systems for more details).

Fitting was done in IDL between field (x, y) coordinates and real (x, y) coordinates.

(X:\Heggie\workspace\Default\fts2_fitting\heggie_portfit.pro).

Included in this fitting is the distortion due to the FTS-2 and SCUBA-2 optics, reversing the horizontal mirroring of each output port image about the port centers, a vertical flip over the x-axis, and a conversion from mm to radians. Using MPFIT2DFUN, polynomials that describe the forward transformation from distorted to undistorted points, as well as polynomials that describe the inverse transformation, were generated. It was found that 4th order polynomials fit the distortion maps within an error of less than 0.01 mm.

7.3. WCS Code

sc2ast_wcs2 was modified to distinguish between subarrays that FTS-2 light falls on (subnums 2-5) and those which the SCUBA-2 transformation routine will be applied to. If using a subarray that includes FTS-2 optics, the function fts2ast_createwcs is called (located in fts2ast.c). The transformation sequence is slightly modified, as the generated polynomials include a vertical flip over the x-axis and a conversion from millimeters to

radians. Also, Port 1 and 2 each have their own set of forward and inverse correction polynomials.

A test program (heggie/programs/wcs_testoutput/fts2_portTrans.c) inputs a points in [i, j] grid coordinates. The AST library carries out the desired transformations, and outputs (Right, UP) coordinates. Transformations are modeled after those in fts2ast.c.

A separate routine or an addition to fts2ast_createwcs2 is needed that will determine the region of a grid of points is within the FTS-2 field of view.

7.4. Fit FTS-2 Polynomials

```
=====
FORWARD -- FIELD X3 -- S8C -- PORT 2 -- SUBNUM 2
```

Field X as a function of Real X and Real Y:

```
3.935148      *1
0.7946079     *x
-0.1262263    *y
0.006119105   *x2
0.003554787   *xy
0.002314147   *y2
-7.198973E-005 *x3
3.539350E-005 *x2y
-0.0001085273 *xy2
-3.122817E-006 *y3
```

```
=====
FORWARD -- FIELD Y3 -- S8C -- PORT 2 -- SUBNUM 2
```

Field Y as a function of Real X and Real Y:

```
1.390747     *1
-0.08256451  *x
0.8191670    *y
0.002192392  *x2
0.002757848  *xy
0.006685674  *y2
-7.792862E-007 *x3
-7.006279E-005 *x2y
-2.280555E-007 *xy2
-9.104939E-005 *y3
```

```
=====
FORWARD -- FIELD X6 -- S8D -- PORT 1 -- SUBNUM 3
```

Field X as a function of Real X and Real Y:

```
-3.862313     *1
0.7916975     *x
0.1277973     *y
-0.006088949  *x2
0.003754012   *xy
```

```
-0.002428307      *y2
-6.922863E-005   *x3
-3.160170E-005   *x2y
-0.0001093737    *xy2
4.678329E-006    *y3
```

```
=====
FORWARD -- FIELD Y6 -- S8D -- PORT 1 -- SUBNUM 3
```

Field Y as a function of Real X and Real Y:

```
1.329764          *1
0.07977744        *x
0.8183589         *y
0.002191212       *x2
-0.002779350      *xy
0.006764802       *y2
1.571388E-006     *x3
-6.864768E-005    *x2y
3.326492E-006     *xy2
-9.122881E-005    *y3
```

```
=====
INVERSE -- REAL X3 -- S8C -- PORT 2 -- SUBNUM 2
```

Real X as a function of Field X and Field Y:

```
-4.635884         *1
1.261577          *x
0.1552550         *y
-0.007763921      *x2
-0.004388896      *xy
-0.003090302      *y2
8.708742E-005     *x3
-2.164918E-005    *x2y
0.0001131093      *xy2
1.123265E-005     *y3
```

```
=====
INVERSE -- REAL Y3 -- S8C -- PORT 2 -- SUBNUM 2
```

Real Y as a function of Field X and Field Y:

```
-1.650477         *1
0.09917511        *x
1.200003          *y
-0.002519505      *x2
-0.003365557      *xy
-0.007328314      *y2
3.861892E-006     *x3
7.632459E-005     *x2y
3.704980E-006     *xy2
0.0001007507      *y3
```

```
=====
INVERSE -- REAL X6 -- S8D -- PORT 1 -- SUBNUM 3
```

Real X as a function of Field X and Field Y:

4.524528	*1
1.261797	*x
-0.1553668	*y
0.007679806	*x2
-0.004540524	*xy
0.003172929	*y2
8.441124E-005	*x3
1.903748E-005	*x2y
0.0001140497	*xy2
-1.244381E-005	*y3

=====
INVERSE -- REAL Y6 -- S8D -- PORT 1 -- SUBNUM 3

Real Y as a function of Field X and Field Y:

-1.550616	*1
-0.09415759	*x
1.198672	*y
-0.002482433	*x2
0.003288798	*xy
-0.007375043	*y2
-4.310079E-006	*x3
7.444857E-005	*x2y
-5.564755E-006	*xy2
0.0001008587	*y3