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Document Title: **FTS-2 Input Port Rotation**

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Change Record

Issue	Date	Section(s) Affected	Description of Change / Change Request Reference / Remarks
0.1	17/08/06	All	First draft
1.0	2/11/06	All	CDR version
2.0	30/07/07	All	Updated to delta-CDR port layout, fixed error in port orientations.

Summary

As a result of the Alt-Az design of the JCMT and the lack of any field de-rotation optics, the SCUBA-2 and FTS-2 optics rotate relative to the JCMT image plane as a function of telescope elevation angle. This rotation is coupled with the normal Alt-Az image rotation and must be removed in the image processing software. This document describes the image rotations in the FTS-2/SCUBA-2/JCMT optical system and the software developed to determine the location of the FTS input ports in Ra-Dec coordinates, as required to properly design the observing tool software for planning FTS-2 observations.

At the time of writing, the image distortions produced by the FTS optics have not been fully calculated. Extra second-order corrections will be required to properly correct for other rotation, magnification, and distortions produced by the FTS itself, but these are beyond the scope of this document.

References

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

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

Contents

1. Introduction

The FTS instrument is mounted at the exit of the telescope elevation bearing at the left Nasmyth. The FTS-2 mechanical design is described in SC2/FTS/MEC/001; the optical design is described in SC2/FTS/OPT/001. In order to provide instantaneous nulling of the atmosphere signal, both input ports of the FTS are placed on adjacent areas of the sky. If the astronomical source is positioned on one input port and there are no sources in the second input port, then the interferogram modulation will only be due to the source signal and not the atmosphere (see SC2/FTS/SYS/004). Proper planning of FTS-2 observations therefore requires calculation of the input port orientation on the sky in order to ensure that the second input port is positioned on a suitable background region.

2. Optical system

There are 6 mirrors in the JCMT system before the FTS, as shown in Figure 1. The telescope image is re-imaged by cabin mirrors C1 through C3 in order to fit the full SCUBA-2 FOV through the elevation bearing tube. These mirrors produce a pupil inside the elevation bearing, and a curved intermediate image plane at the exit of the bearing tube where the FTS is located. All of the optics before the FTS rotate as a unit as the telescope rotates in elevation.

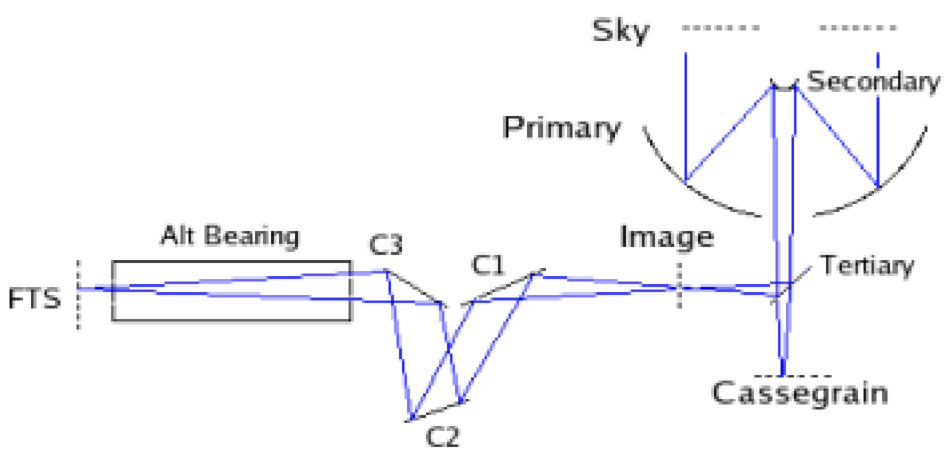

Figure 1. Schematic of the intermediate image planes in the JCMT optics. The dotted lines represent the four different image planes relevant to FTS-2. A coordinate reference frame is defined at each image plane. The Cassegrain frame is at a virtual image plane assuming that the tertiary mirror did not exist.

It was convenient to design the FTS so that the two input ports are aligned on two adjacent quadrants of the SCUBA-2 FOV, as shown in Figure 2. The two upper quadrants of the bearing tube intermediate image are used for the input ports in order to provide more space for the FTS optics, and allow the possibility of using the lower two quadrants for photometric measurements during FTS-2 observations. The orientation of the FTS ports relative to the SCUBA-2 arrays is static.

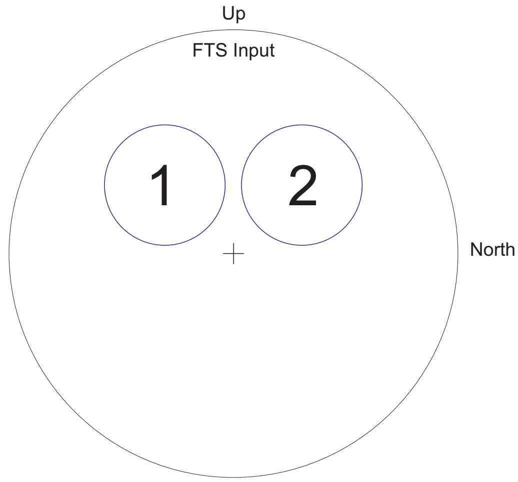

Figure 2. The geometry of the FTS ports at the FTS-2 input image plane, when the telescope elevation axis is aligned east-west. In this diagram, light travels out of the paper towards the FTS. The origin corresponds to SCUBA-2 optical axis. The FTS ports occupy the upper two quadrants of the bearing tube intermediate image plane.

The output port images are reproduced at the input image plane, and each output port contains the interferometric difference of both input ports. The parity of the mirror reflections inside the interferometer leads to a horizontal mirroring of each output port image about the port centres. Figure 3 shows the output of the FTS, with the superimposed port images shown in light grey.

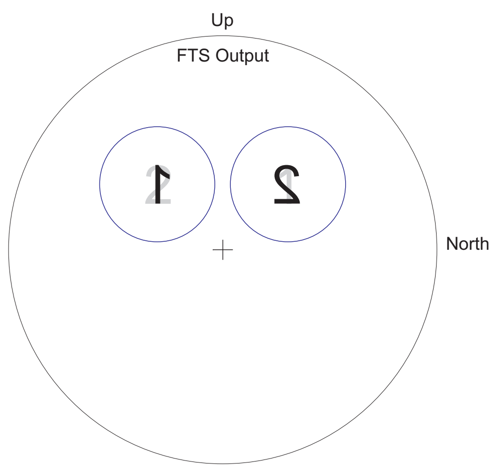

Figure 3. The output of the FTS is returned to the SCUBA-2 optical system just beyond the FTS input image plane. Each output port image is mirrored horizontally about the centre of the port, and each output contains the superposition of both input ports as shown by the light grey numbers.

The 450 μm and 850 μm beams are split by a dichroic just before the arrays, resulting in a flip in the image about the horizontal axis. From the transformations described in (SC2/SOF/S200/042), port 1 maps onto the s8d and s4a arrays, and port 2 maps onto the s8c and s4b arrays, as shown in Figure 4.

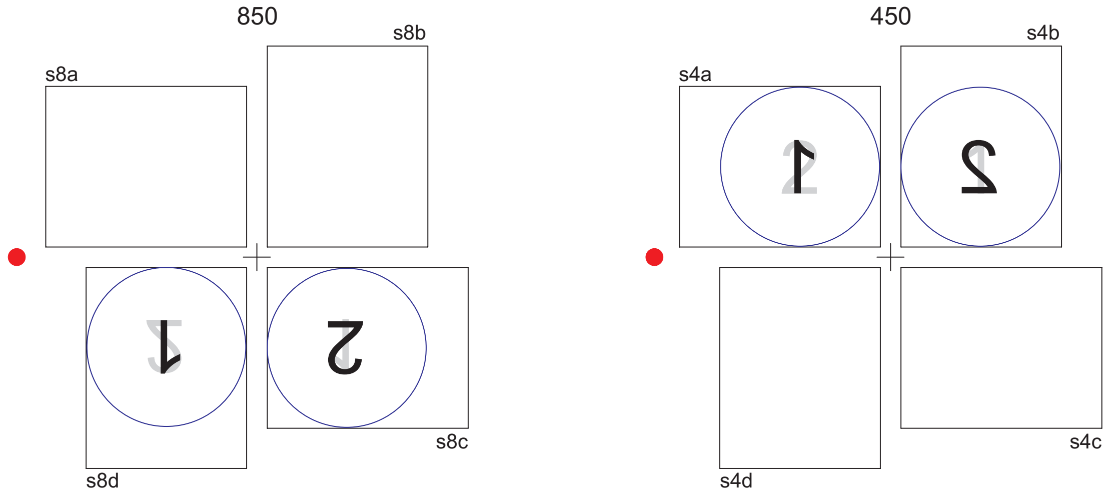

Figure 4. The FTS-2 output port orientation (blue circles) on the SCUBA-2 detector arrays. The arrays are seen from behind, with light travelling out of the paper. The image in each port is mirrored about the vertical axis relative to the non-FTS image, and the two ports are combined with each other by mirroring about the telescope optical axis (as shown by the light grey numbers).

3. Intermediate coordinate frames

In order to describe the port orientation at the various image planes, the coordinate systems must be defined. In each case, the coordinate systems are defined as right-handed with x being positive to the right and y being positive upwards when looking in the negative z direction (towards the input of the telescope) and the telescope is pointed at the horizon.

In the optical path between the sky and the FTS there are two intermediate foci, a rotation about the elevation axis, and 6 mirrors. A list of the coordinate transformations as one travels from the FTS image plane to the sky is given below.

1. ***FTS image plane***
2. Counter-clockwise rotation at the elevation bearing as the telescope rotates in elevation from 0° to 90°
3. 180° rotation when crossing the pupil in the elevation bearing
4. Flip about x axis at C3
5. Flip about x axis at C2
6. Flip about x axis at C1
7. ***Intermediate image plane***
8. Flip about x axis at Tertiary
9. 180° rotation when crossing the pupil in the telescope
10. ***Sky image plane***
11. Ra-Dec coordinate frame

Since two flips about the same axis will cancel each other out, step 4 cancels with step 5, step 6 cancels step 8, and the two rotations (steps 3 and 9) cancel each other out. This leaves step 2 as the only transformation to convert from the FTS image coordinate frame to the sky image plane as defined above.

4. Image rotation

Figure 5 shows the location of the two FTS input ports in each of the reference frames described above for telescope elevations of 0° and 90°. Between the FTS input frame and the Sky frame, there is only a counter-clockwise rotation equal to the telescope elevation angle. This rotation must be added to the normal Alt-Az to Ra-Dec coordinate transformations.

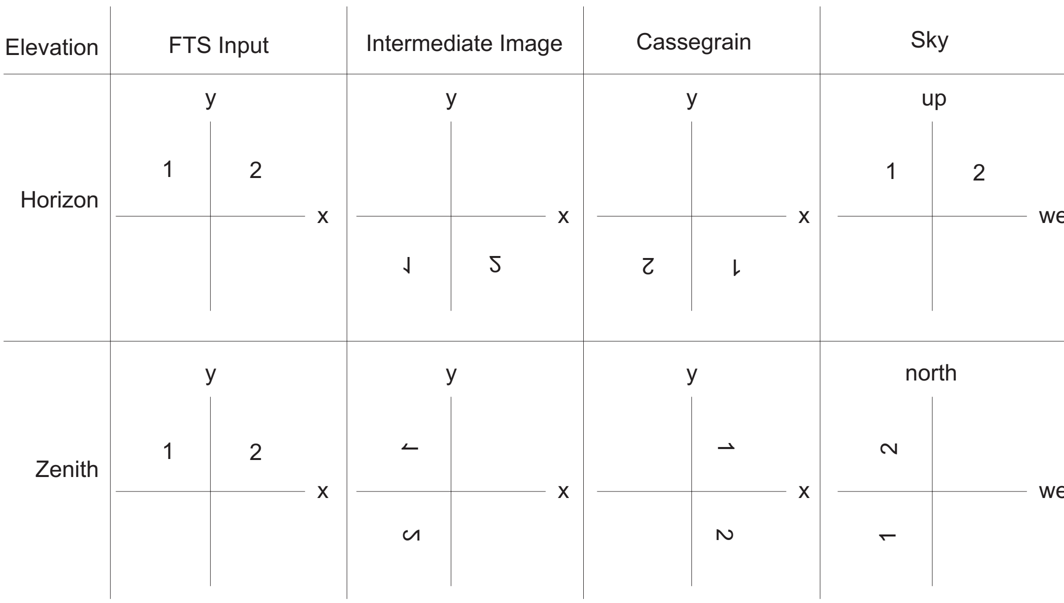

Figure 5. Port orientations for the various coordinate frames with the telescope at the horizon and at zenith. Light travels in the positive z direction in each coordinate frame.

5. Ra-Dec coordinates

After properly rotating the FTS ports, the coordinates are converted to Ra-Dec. Note that when plotted in Ra-Dec coordinates, the ports are naturally no longer expected to be circular. Figure 6 shows examples of the FTS ports mapped onto the Ra-Dec coordinate frame for various positions in the sky.

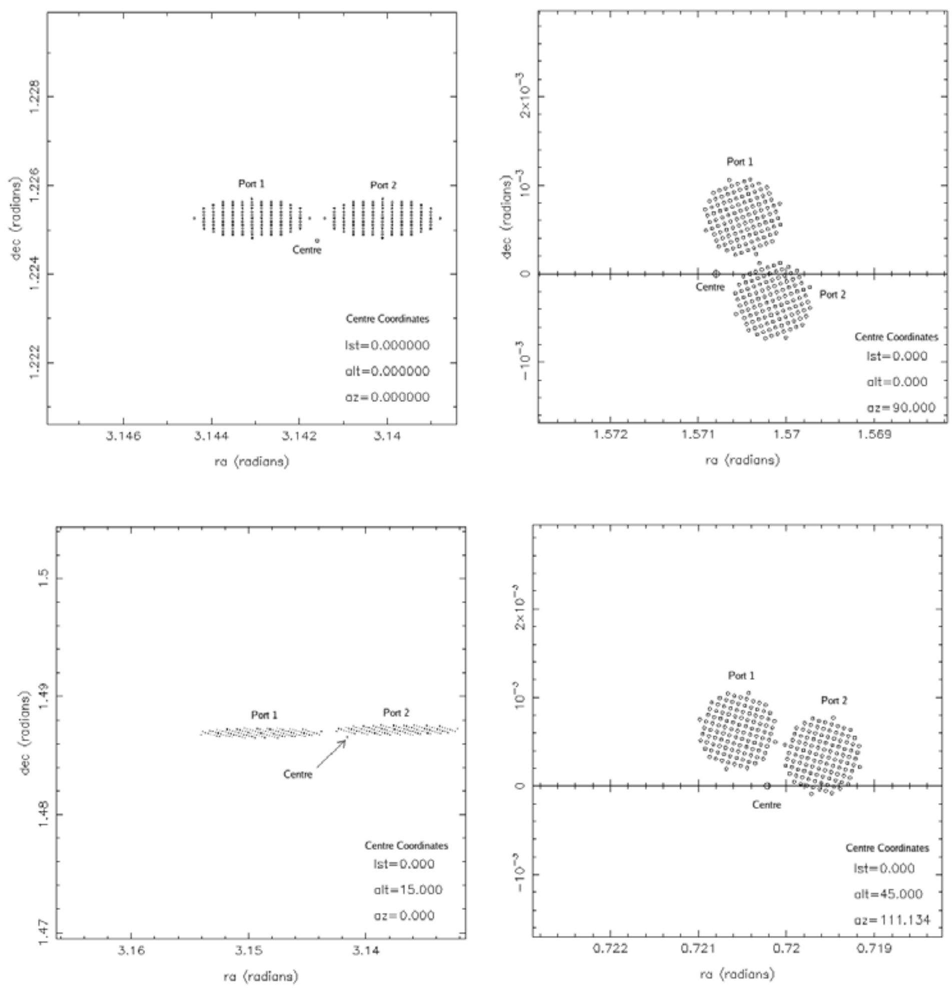

Figure 6. Examples of the FTS input ports mapped onto the Ra-Dec coordinate frame. Small circles are schematic representations of the pixel grid. The centre of the SCUBA-2 FOV is shown for reference.

6. Port Rotation Program

A C program has been written that calculates the FTS port positions given the coordinates of the centre of the SCUBA-2 FOV. The program is designed to be included as a library in other programs that require the positions of the ports in Ra-Dec coordinates. The program uses some code described in SC2/SOF/IC210/01, which uses the AST astronomy library available in the Starlink package (as ast.h) to do the matrix transforms when converting between coordinate frames.

Note that the additional rotation and polynomial distortion present in the FTS output images on the subarrays, described in section 2, is not currently accounted for in this rotation algorithm.

6.1. Algorithm description

1. Set up the rotation matrix for the telescope elevation angle. In a frame similar to the one seen in Fig. 3 the rotation is counter clockwise for positive altitude. The image frame has an additional flip because its rotation is in the opposite direction.

2. Apply the transformation to the input coordinates and produce the coordinates in the sky frame.

3. Convert from the sky reference frame (x and y defined earlier) to Alt-Az:

   $\Delta Az = \arctan(\tan(x)/\cos(Alt))$

   where Alt is the altitude of the telescope axis.

   $\Delta Alt = y$

   since Alt and the y coordinate in the sky reference frame are both measured along a great circle from the horizon to the zenith.

4. Convert to Ra-Dec. To do this the function needs to know the altitude and azimuth of the telescope axis. The altitude is given and the azimuth can be calculated from altitude, right ascension, and declination. From the altitude and azimuth of the centre, the actual altitude and azimuth of the location is calculated and then converted to Ra-Dec.

It should be noted that the code assumes that the pointing is defined by the centre of the SCUBA-2 FOV, and not the centre of the FTS port(s). This means that if the pointing is calculated by entering the desired coordinates of an input port and then offsetting by the distance to the optical axis, there will be an error of ~0.075" in the calculated position of the second input port as a result of the extra field rotation caused by offsetting in elevation (measured in the sky frame). This error is a small fraction of the roughly 6" pixel spacing. In Ra-Dec coordinates, the error will depend on the position in the sky. For example, with the telescope at the horizon facing north (Alt = 0, Az = 0, Dec = ~70°) there is an error of 0.15" in Ra and 0.052" in Dec. When the altitude is moved to 15° (Dec = ~85°), the errors in Ra and Dec becomes 0.78" and 0.045".

A method called 'reverserotation' has been developed which takes the coordinates of a port and returns the location of the centre. The calling sequence is identical to the 'rotation' method except it takes the coordinates of a port. The xpos and ypos values are the same as in the 'rotation' method. An example of the algorithm for port 1 is given below. Subscript 'c' denotes coordinates of the centre, whereas subscript 'p' denotes coordinates of the port.

1. Define *lst* as the local sidereal time and *centreofport* as the angular value for the centre of the port ($5.0217 * 10^{-4}$ radians).

2. Calculate Alt_{p1} from given Ra_{p1}, Dec_{p1}, and *lst*.

3. Use rotation method with Alt_{p1}, Ra_{p1}, Dec_{p1}, *lst*, *-centreofport*, *-centerofport*. Note the minus signs on the *centreofport* values, this means that the centre of the FTS FOV is being estimated via the port location.

4. The rotation method returns Ra_c, and Dec_c with a small error.

5. Calculate Alt_c from Ra_c, Dec_c, and *lst*.
6. Use the rotation method to calculate the location of port 1 using Alt_c, Ra_c, Dec_c, *lst*, *centreofport*, *centreofport*. Call the returned port coordinates Ra_{p1}', and Dec_{p1}'.
7. Comparing the returned values with Ra_{p1} and Dec_{p1} will provide an estimated error for the centre coordinates. Call the errors ΔRa and ΔDec.
8. Get a new location in the sky by subtracting the errors from the original Ra_{p1} and Dec_{p1}. Call these new values Ra_{p1}'' and Dec_{p1}''.
9. Calculate the new altitude, Alt_{p1}', from Ra_{p1}'', Dec_{p1}'', and *lst*.
10. Calculate the centre location with the 'rotation' method using Alt_{p1}', Ra_{p1}'', Dec_{p1}'', *lst*, *-centreofport*, *-centreofport*. The error in the resulting Ra and Dec should be less than ~ 10^{-5} arcseconds.

6.2. Calling sequence

The calling sequence for this program is given below:

```
double *rotation(double alt, double ra, double dec, double lst, double xpos, double ypos)
```

The input parameters are given in the following table. The routine outputs the converted Ra-Dec coordinates (in radians) as a pointer to an array of doubles.

Table 1. Input parameters. Units are radians.

Parameter	Description
alt	The altitude of the centre of the SCUBA-2 FOV
ra	The right ascension of the centre of the SCUBA-2 FOV
dec	The declination of the centre of the SCUBA-2 FOV
lst	The current local sidereal time
xpos	The x coordinate of the spot of interest from the FTS input coordinate frame. Centre of port 1 is at $-5.0217*10^{-4}$ radians
ypos	The y coordinate of the spot of interest from the FTS input coordinate frame. Centre of port 1 is at $5.0217*10^{-4}$ radians

6.3. Notes on Using the Program

When the ports are plotted in Ra-Dec or Alt-Az frames they are not necessarily circular. In these frames the shape of the port depends on the position in the sky. The actual size of the FTS ports is fixed in angular units relative to the SCUBA-2 FOV.

It should be noted that the code contains commented sections of the original SCUBA-2 coordinate transformations that are not used. These sections are retained as a provision for future modifications.

There are several constants (e.g. latitude of JCMT) used in the program; these are located near the top of the code. If it is not obvious, the program only does one port at a time, either the source port or the background port. The program also requires the library coordtrans.h, which contains math functions for the transformations from Alt-Az to Ra-Dec and back.