JCMT

Coordinate

Concepts

Contents:

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1 Source Coordinates and Mapping

This document describes the the various coordinate systems used at JCMT. The astronomer needs to understand these concepts in order to control where the telescope points at each phase of an 'observation'. This task is met (and accomplished) when compiling the observation scripts (MSBs). Telescope positions are described by a combination of the target position and coordinate frame, a locally defined coordinate system centred on the target, and offsets from that position, as well as a description of how the secondary mirror must behave at each moment. Hence the second half of this document describes the behaviour of the SMU.

The concepts in this document are most easily envisaged in respect to the use of single-pixel receivers although they extend without much adjustment to use with areal detectors.

1.1 Coordinate Frames

Source positions (coordinates) may be specified to the JCMT control system in the following astronomical coordinate frames:

- Right Ascension – Declination (RA/Dec), for the epochs 1950, 2000, and current date. These coordinate frames are known to the operator as `RB`, `RJ` and `RD` respectively.
- Galactic longitude and latitude (ℓ/b). Known as `GA`.
- Equatorial (Hour Angle – Declination; HA/Dec; `EQ`).
- Altazimuth (azimuth – elevation; Az/El; `AZ`).

Most astronomers will specify positions in RA/Dec; for some purposes galactic coordinates will be appropriate. Note that for some objects closer than about 200 parsec, it may be necessary to apply corrections for proper motion, particularly if 1950 coordinates are used. RA/Dec and ℓ/b coordinate frames are *left-handed*; *i.e.* for a source at **S** (see Fig. 1) the latitude axis (declination, galactic latitude) points towards the coordinate frame north pole, and the longitude axis (Right Ascension, galactic longitude) is at position angle 90 degrees with respect to it[1]. The approximate conversion between RA/Dec and ℓ/b, and vice versa, can be derived from Fig. 2. The telescope position is given in azimuth and elevation (or alternatively, in HA/Dec), and is continuously updated by the control system to allow for the motion of the Earth in order to track a source position given in RA/Dec (or ℓ/b). Note that Az/El and HA/Dec are *right-handed* coordinate systems, as shown in Fig. 3; the position angle of the longitude axis is thus -90 °. The azimuth zero point is geographic North, while hour angle is measured from the local meridian.

Figure 4 shows the approximate conversion between Hour Angle and Declination and Azimuth and Elevation for the latitude of the JCMT. To obtain the hour angle HA of a given source at right ascension RA at a local sidereal time of LST, use:

$$HA = LST - RA$$

[1]Position angles throughout this document are measured in accordance with convention in the anti-clockwise direction

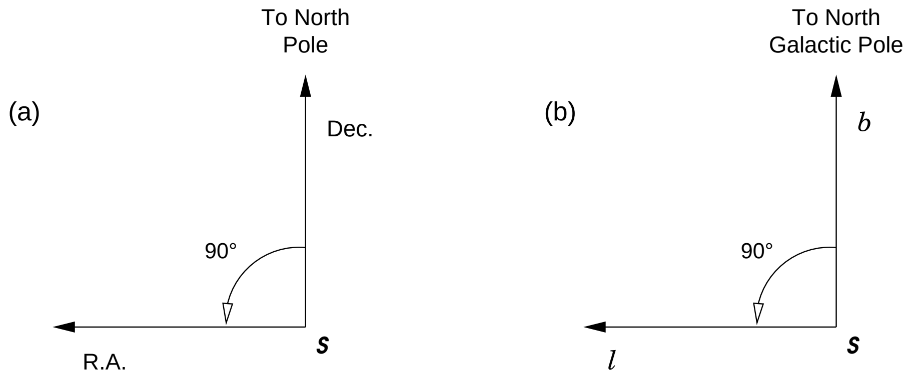


Figure 1: Left-handed coordinate systems (a) Right Ascension–Declination (RA/Dec), (b) galactic (ℓ/b). Note that the position angle of the longitude axis with respect to the latitude axis is 90°.

RA/Dec and HA/Dec coordinates are given to the JCMT system in hours, minutes, and seconds, and degrees, minutes, and seconds (*e.g.* $12^h34^m56.7^s$, $-13°52'43''$). Altazimuth and galactic coordinates are specified in degrees, minutes, and seconds (not decimal degrees, as is more usual).

As described in the primer for using the JCMT Observing Tool

http://www.jach.hawaii.edu/software/jcmtot/

coordinate strings fed via the MSB to the JCMT operating system must use colon separators, so a valid RA string will look like this:

12:34:56.789

1.2 Coordinates of Solar System objects

The JCMT control system has access to ephemerides which allow the tracking of the Sun, Moon, and the planets to an accuracy better than an arc second. The observing script (MSB) has only to specify the name of the desired object. For solar system objects other than the above (e.g. comets) the script must also provide the orbital elements, which are obtainable from

http://ssd.jpl.nasa.gov/horizons.cgi

1.3 Creating Source Catalogs

In order to replicate a set of observing demands from one script (MSB) to another or to many others, the user can make a file which contains all target source positions. The file should mimic the structure in the JCMT pointing catalog

http://www.jach.hawaii.edu/JCMT/telescope/pointing/pointing_catalog

The mechanism for achieving the replication is described in the JCMT OT primer

http://www.jach.hawaii.edu/software/jcmtot/advanced.html#replication

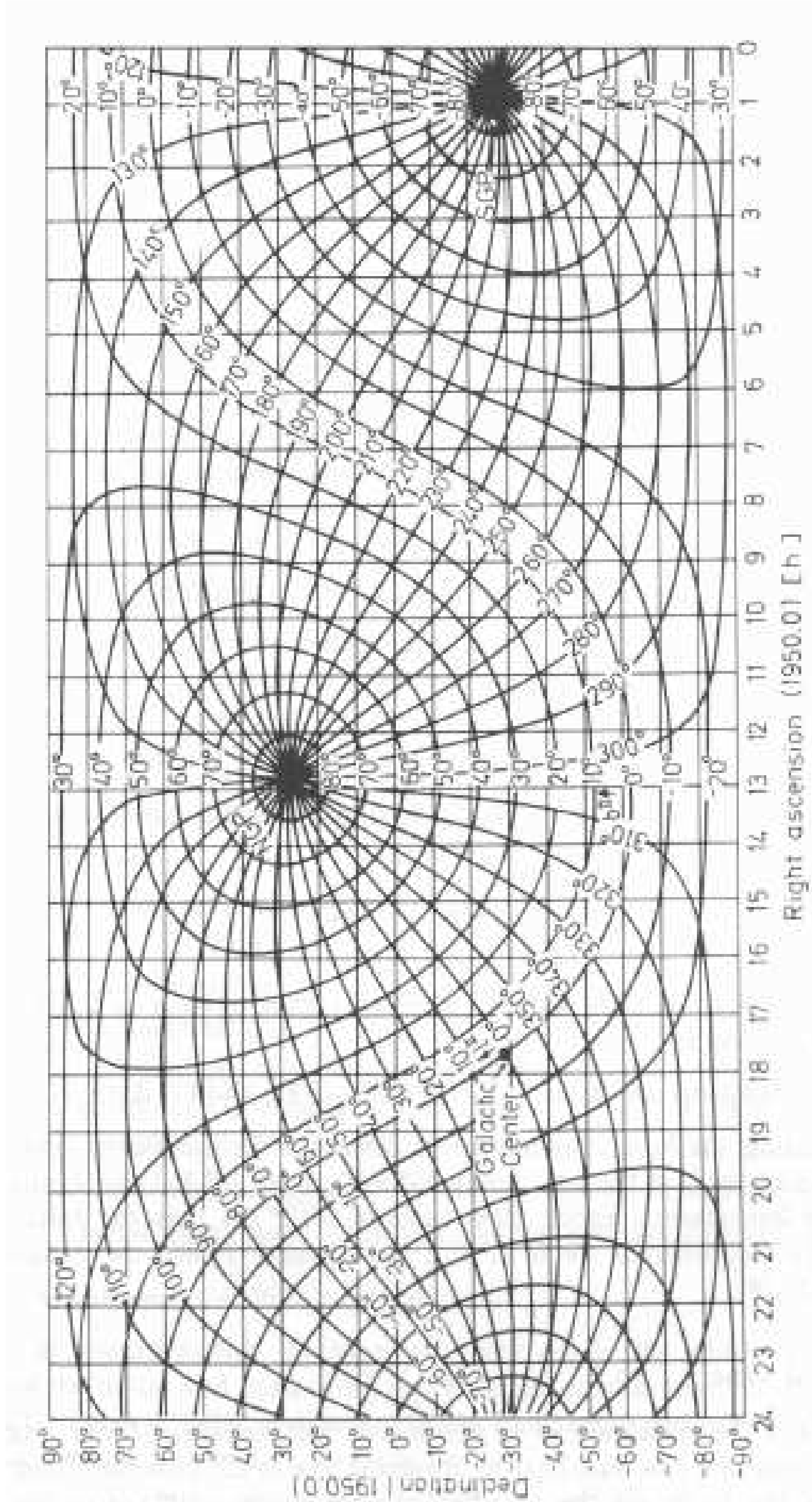


Figure 2: Conversion between RA/Dec and ℓ/b, taken from *Astrophysical Formulæ* (K.R. Lang, Springer-Verlag, second edition, 1987).

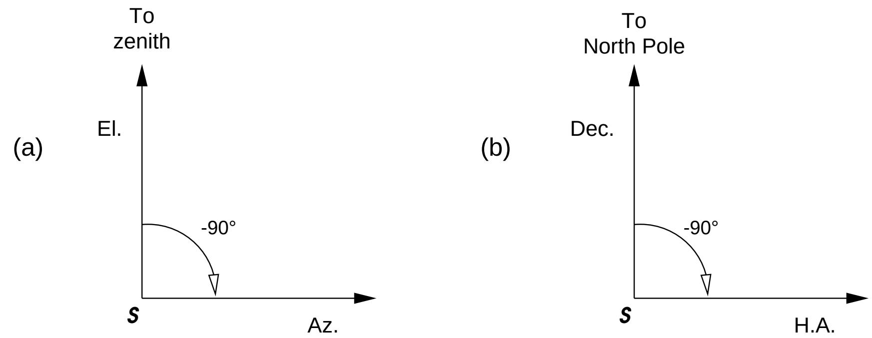


Figure 3: Right-handed coordinate systems. (a) Azimuth–Elevation and (b) Hour Angle–Declination coordinate frames. The position angle of the longitude axis with respect to the latitude axis is $-90°$.

1.4 Source Availability

The utility `SOURCEPLOT` will display the positions of the Sun, the Moon, the major planets, and (by default) the targets in the JCMT Pointing Catalog, but also (by input) any other target. The display is malleable, and can show, for instance elevation or azimuth as a function of time or can show the position(s) projected onto the dome of the sky. The plots show daily tracks with 15-minute markers, and the utility allows for change of date.

1.5 Mapping, offsets, etc.

For anyone who intends to make maps in spectral-line or continuum modes, or specify positions offset with respect to the given source position, it is necessary to understand the way the JCMT system handles relative coordinates. The concept of the "cell" is central to this topic. In a mapping grid the cell is the basic element of the grid, the same cell parameters are used to define offsets from the source position.

1.5.1 Understanding the Cell concept

A cell is defined in terms of a coordinate frame, with unit vectors representing the longitude and latitude directions. The cell may be rotated with respect to its local coordinate frame, or 'local vertical', and the longitude and latitude unit vectors do not have to be orthogonal to one another (this latter feature is rarely used, and discussion on it is deferred to section 1.5.8). It is important to note that the cell (local) coordinate frame does *not* have to be the same as that in which the source position is specified. In other words, although one may select a local RA/Dec(1950) coordinate frame for a cell for a source whose position is specified in RA/Dec(1950), it is also common to specify the cell local coordinate frame as Az/El for the same source. This is, for example, the normal procedure in pointing observations.

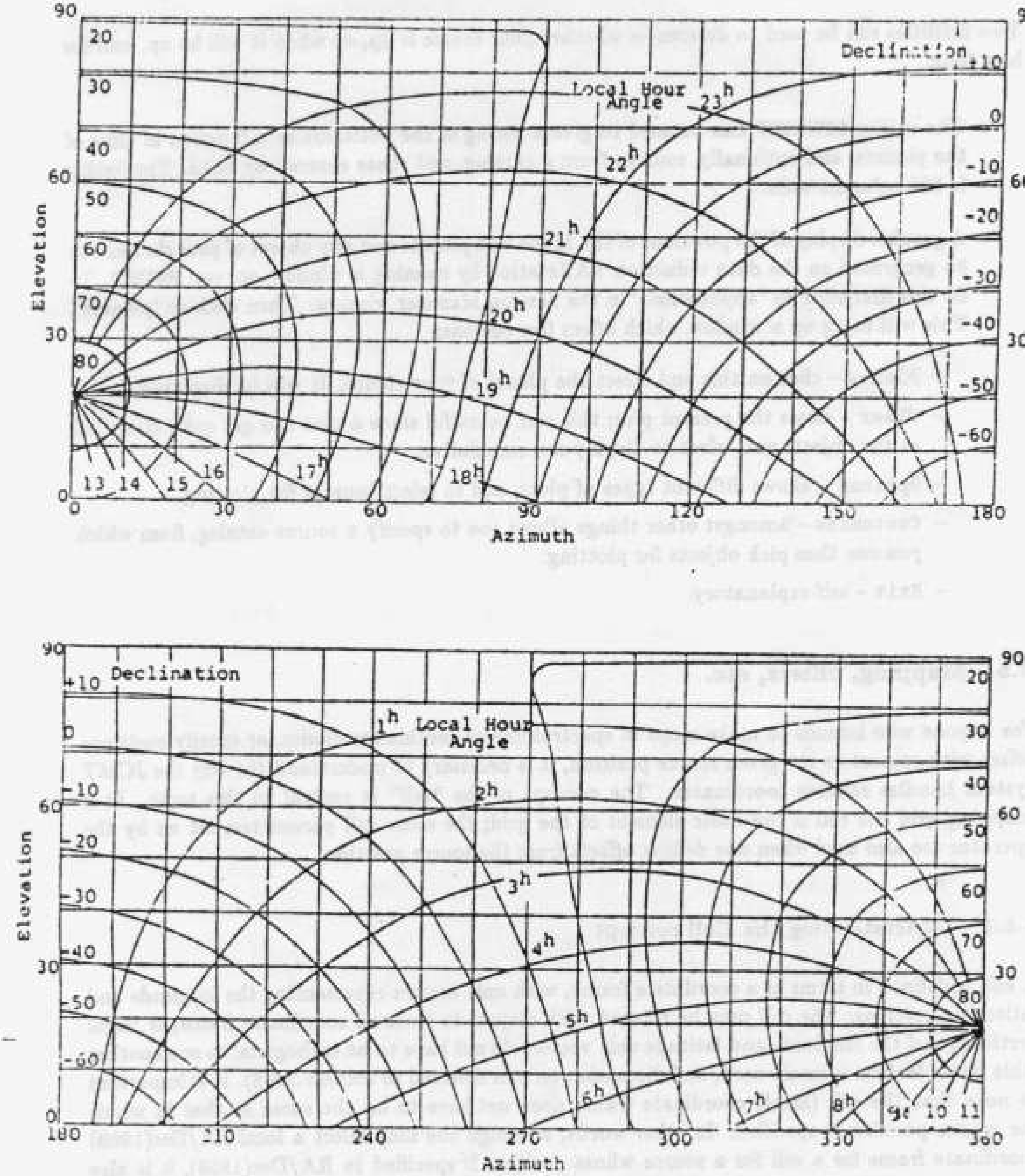


Figure 4: Conversion between Hour Angle–Declination and Azimuth–Elevation for the latitude of the JCMT.

Units
The lengths of cell axes are always given in arcseconds, and the position angle in degrees.

In the two examples below, for a source whose position is given in the RA/Dec frame, Δx and Δy describe the lengths of the unit vectors along the longitude and latitude axes respectively, and θ_y is the position angle of $\vec{\Delta y}$ with respect to the local vertical[2]; cells are defined by the number set $(\Delta x, \Delta y, \theta_y)$. (This number set is known within the MSB Offset iterator for a grid(-map) as (p,q,PA)). Cell axis coordinates in the following figure(s) are shown primed, *e.g.* RA′, Dec′, for an RA/Dec cell.

RA/Dec cell. In this case the local vertical coincides with a a line of declination passing through the source, and points to the North Pole. See Figure 5 for examples.

Az/El cell. Figure 6 shows three examples of cells defined in the Az′/El′ system. There is an obvious difference in this case, however, since as the source is tracked across the sky, the local Az'/El' cell moves with it, but *rotates* with respect to the source. For sources north of declination 19°50′ (the latitude of the JCMT), at transit the declination axis is pointing in the opposite direction from the elevation axis. This can be a source of confusion if one uses a cell defined in Az′/El′. More on this below.

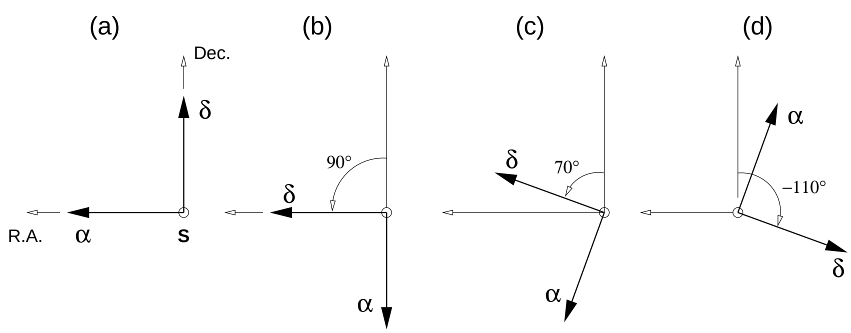


Figure 5: Examples of cells in RA′/Dec′ at various position angles: (a) (10″,10″,0°), (b) (10″,10″,90°), (c) (10″,15″,70°), and (d) (10″,15″,-110°), or (10″,15″,250°). The local (cell) RA and Dec axes are indicated by RA′ and Dec′. Note that case (b) places the local (cell) latitude (Dec′) along the source RA axis, and the local longitude (RA′) along the negative Dec axis.

[2] Δx, Δy and θ are known to the control system as `cell_x`, `cell_y` and `cell_v2y` respectively

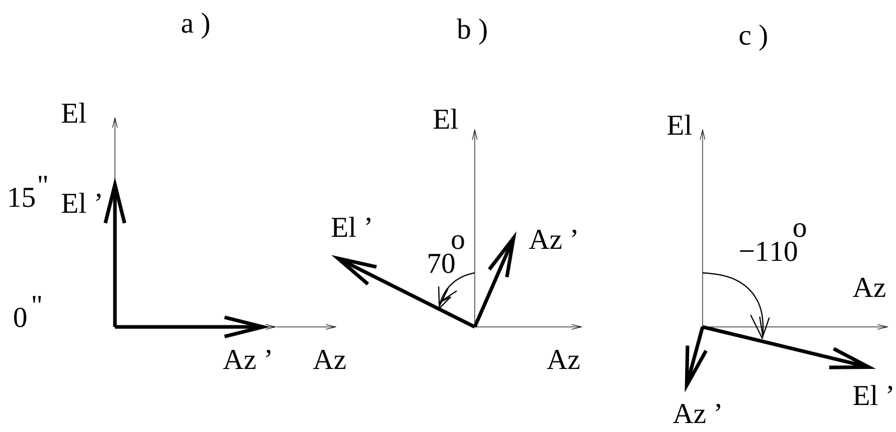


Figure 6: Examples of cells in Az′/El′: (a) (15″,15″,0°), (b) (10″,15″,70°), and (c) (7″,15″,-110°).

1.5.2 Allowable cell coordinate frames

The available choices of cell coordinate frames are in fact restricted by the coordinate frame in which the source position is given. One can always define a cell having the same coordinate system as that of the source, and it is always possible to use an Az′/El′ cell in combination with any other coordinate frame. These two situations will be those which the astronomer will almost always wish to use. However, some other combinations make no sense, and the control system will not permit their use. For example, one cannot use an RA′/Dec′(1950) cell in combination with an RA/Dec(date) frame. A summary of the allowable configurations is given in Table 1.

Table 1: Allowed Source–Cell Coordinate Frame* Combinations (indicated by ♡; not allowed shown by –).

Source frame	Cell (local) frame					
	AZ	EQ	RB	RD	RJ	GA
AZ	♡	–	–	–	–	–
EQ	♡	♡	–	–	–	–
RB	♡	–	♡	–	♡	♡
RD	♡	–	–	♡	–	–
RJ	♡	–	–	–	♡	♡
GA	♡	–	–	–	♡	♡

*Coordinate frames are identified by symbols familiar to the JCMT operator: AZ is Az/El, EQ is HA/Dec, RB, RD, and RJ are RA/Dec for epoch 1950, date and 2000 resp., and GA is ℓ/b.

1.5.3 Offset Source Positions

Once a cell is defined, an offset position can be described in terms of cell units. For instance, if the cell parameters are $(\Delta x, \Delta y, \theta_y) = (10'', 10'', 0°)$, the point $(-3,2)$ describes the offset $(-30'',20'')$ with respect to the source position. This situation is shown in Figure 7. Note that these offsets are true angular distances; to obtain the actual change in longitude one must divide by cos(latitude). Hence if the total RA′ offset is 30″, then this results in an offset in RA of 30/cos(Dec) for a source whose position and cell are both in RA/Dec.

Note: It is useful often when dealing with offsets to specify a cell size of 1″ in each dimension. Then offsets may be directly given in arc seconds.

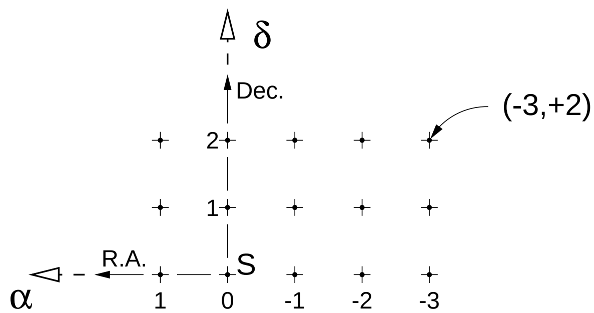


Figure 7: An example of a positional offset using an RA′/Dec′ cell in an RA/Dec source frame.

The result of offsetting from an RA/Dec source using an Az′/El′ cell definition depends on the hour angle of the source and thus the offset position of the relative to the source changes in RA and Dec with time. Thus one should not use an offset defined in Az′/El′ unless confident that the changing position will not influence the results. In addition the same Az′/El′ offset has different effects also for different declinations. This is illustrated in Fig. 8.

1.5.4 Reference Position Offsets

When taking *total power* spectra (such as during position-switched observing, when the observing time is split between the source position and a reference position), *the reference position offset from the source position is specified in arc seconds*, not cells. This can be a source of confusion if one is not wary: Are the reference offsets displayed in cell units or arcseconds on the telescope status screen?

1.5.5 Defining Grid Maps

A grid (or grid map) is in effect an array of offset points, and thus is described readily using the cell as the basic unit. One need only specify the dimensions of the grid in terms of the number of cells in the local longitude and latitude coordinates, N_x and N_y respectively. The 5×3 RA/Dec grid shown in Figure 9(a) demonstrates the order in which grid points are numbered. N_x and N_y

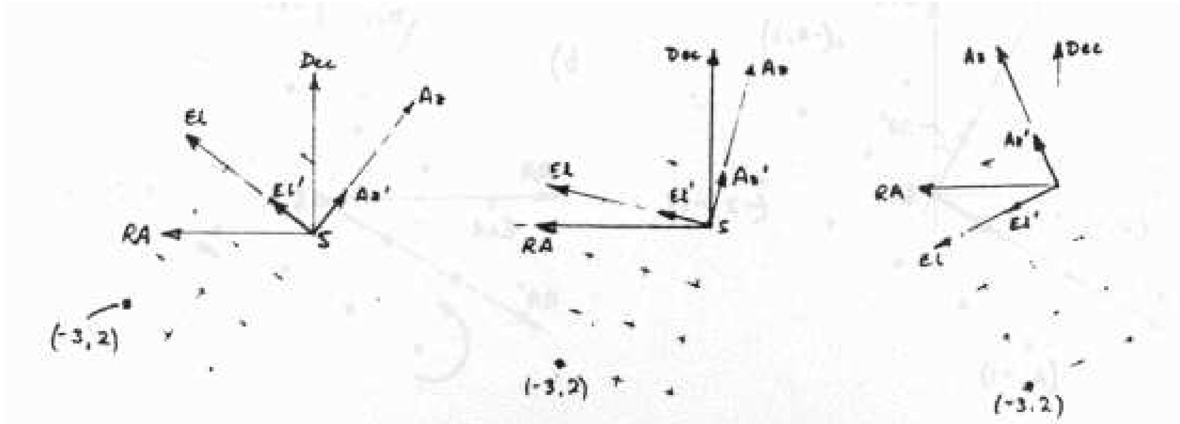


Figure 8: The offset (−3,2) for an Az′/El′ cell (10″,10″,0°) for three sources at Dec = −15, 15, and 50° 3 hours after transit. Note the different position angles of the Az′/El′ cell with respect to the source coordinate frame.

do *not* have to be odd numbers. For instance, a 2×2 grid contains four points $\pm\Delta x/2$, $\pm\Delta y/2$ from the source position; *i.e.* for either N_x or N_y even, the map centre lies midway between the central two points in the direction(s) with even numbers of grid points. One should however avoid even-numbered grid dimensions, unless this is really desired, because of the potential for confusion.

The points of a map are observed starting with the corner having the largest negative (x, y) offsets by stepping first in cell longitude, and incrementing in cell latitude until the grid is complete. Thus cell longitude is the 'fast', and latitude the 'slow' coordinate. It is possible to scan longitude rows in either the same direction, or in alternating directions ('row-reversal', false, or true, respectively). The example in Figure 9(b) shows the order in which points in a grid are observed when row-reversal is set to 'true'.

1.5.6 Offsetting the map centre

The centre of a map may be offset from a given source position in cell units. An example of this is shown in Figure 10.

1.5.7 Practical Examples

(To repeat the caveat at the beginning of this document: this example was written assuming the use of single-pixel receivers, but the concepts are applicable when using array detectors).

Let's say you have a spiral galaxy the major axis of which has a position angle of 38° (North through East). You wish to map the nuclear region in CO(3–2), and inspect the tangential points of the spiral arms in the same line. The optical image of the galaxy is about 3′ across. You know that the beamwidth of the JCMT at 345 GHz is about 15″, but because the lines are weak and time limited, you decide to undersample spatially by choosing a cell size of 10″ × 10″.

I. A Map of the Central Region. You choose a 9×5 grid, parallel with the major axis, as suitable for this task. As shown in Figure 11, one would generally choose an RA′/Dec′ cell with

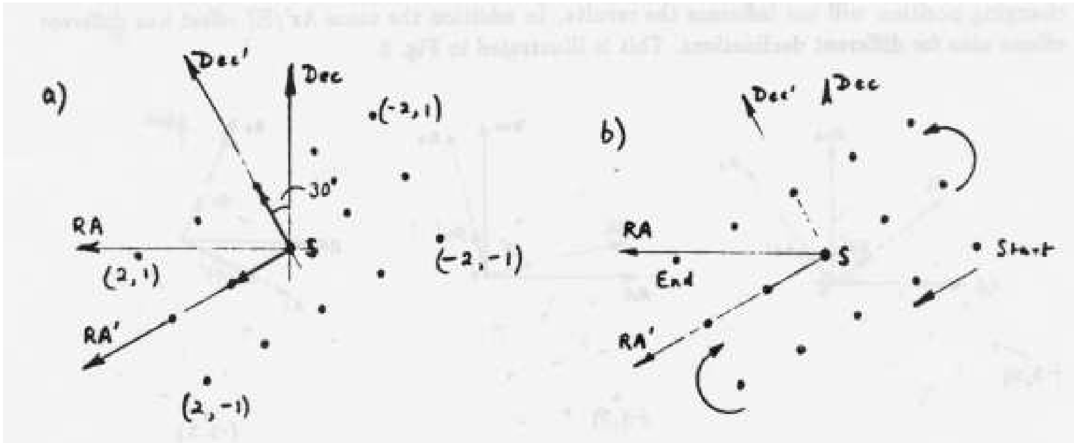


Figure 9: (a) A 5×3 RA′/Dec′ grid showing the way in which grid points are numbered. The cell definition is (10″,10″,30°). (b) The same grid, showing the order in which grid points are observed by the JCMT control system when 'row-reversal' is on. The source position is indicated by **S**.

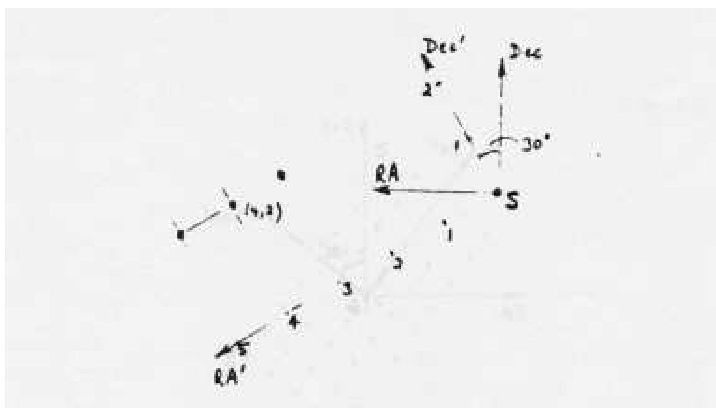


Figure 10: An example of an offset map centre. The 3×1 RA′/Dec′ grid is offset by $\Delta x = 4$, $\Delta y = 2$ from the source at **S**. The cell definition is the same as in Fig. 9.

position angle $\theta_y = -52°$, in which case mapping would begin at **A**, proceeding in rows parallel to the major axis, until reaching **C** (if 'row-reversal' is set on). Alternatively, one could map perpendicular to the major axis, beginning at **B**, by setting $\theta_y = 38°$. Still other alternatives are of course possible.

II. Maps of the Spiral Arms. Because the spiral arms might be more extended away from the major axis than the nuclear region, you choose two 9×3 grids perpendicular to the major axis, centered at the offset positions $\mathbf{S}_1$ and $\mathbf{S}_2$ displaced $\pm 50''$ from the galaxy nucleus, as shown in Figure 12. One solution to this is to choose $\theta_y = 38°$. Then the grid centered on $\mathbf{S}_1$ requires the map offsets to be set to $(x, y) = (0, -5)$, and for that at $\mathbf{S}_2$ $(x, y) = (0, 5)$.

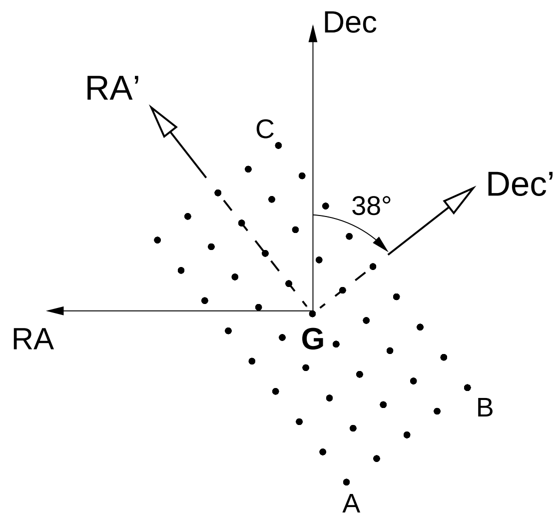


Figure 11: Example of a grid set up to map a galaxy centered at **G**. The galaxy has a position angle of 38°. By setting $\theta_y = -52°$, the galaxy is mapped starting at **A** in rows parallel to the major axis, and ending at **C** if 'row-reversal' is set. If $\theta_y = 38°$, the map starts at **B** and continues in rows perpendicular to the major axis.

1.5.8 Non-orthogonal Cell Axes

It is possible to specify a cell in which the longitude and latitude axes unit vectors are non-orthogonal. This may be done in two different ways:

1. By giving the coordinates of the ends of the new unit vectors in terms of the orthogonal frame. Thus, as shown in the example in Figure 13(a), one must specify (x_1, x_2) to re-define the longitude axis, and similarly (y_1, y_2) for the latitude axis.[3] The subscripts 1 and 2 refer to the original cell longitude and latitude axes respectively. The original (orthogonal) axis description is thus (10,0), (0,10) for a $10 \times 10''$ RA$'$/Dec$'$ cell, with $\theta = 0°$.

2. By specifying the position angles (measured anti-clockwise, as always) of both the x and y cell unit vectors with respect to the local vertical, θ_x and θ_y (see Figure 13(b)).[4] Thus the standard orthogonal axes would be given by $\theta_x = 90°$, $\theta_x = 0°$ for an RA$'$/Dec$'$ cell. The lengths of the cell unit vectors are defined in the usual way.

A grid based on a non-orthogonal cell definition is shown in Figure 14. It is possible that this flexibility in cell (grid) definition has never actually been used in anger at JCMT !

1.6 Grid definitions within an MSB

The definition of the cell and grid for an MSB (minimum schedulable block) is done in the 'Offset' iterator but, you will see, this merely generates a list of offset positions. Once the cell has been defined it is possible to expand the map essentially *ad infinitum* either by adding points in blocks

[3] x_1, x_2, y_1, and y_2 are known as `xaxis_1, xaxis_2, yaxis_1` and `yaxis_2` to the JCMT control system.
[4] The angles are known as the parameters `cell_v2x` and `cell_v2y` in the JCMT control system.

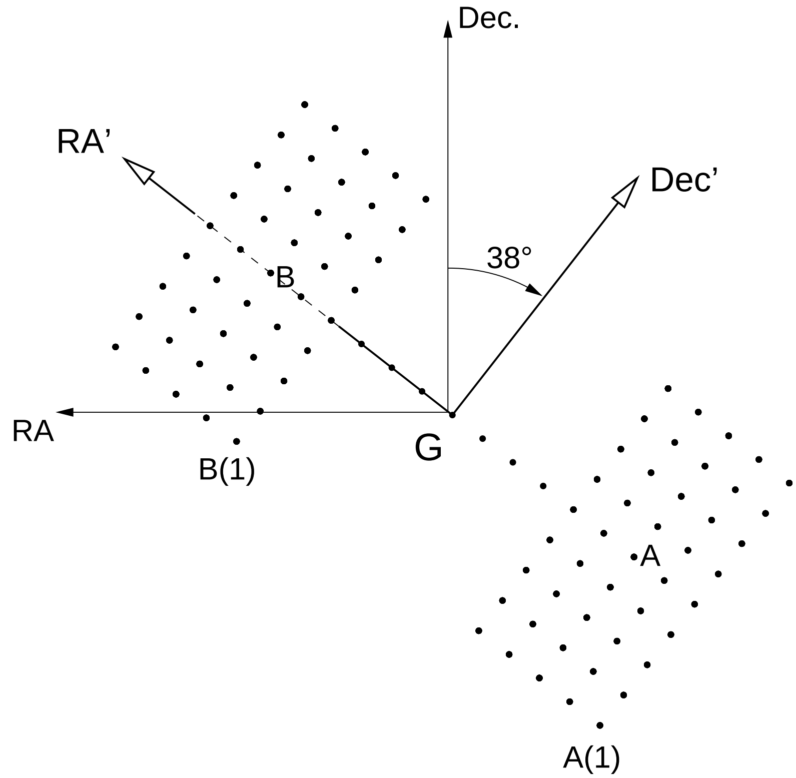


Figure 12: Mapping two offset grids around the galaxy at **G**, both centered on the major axis, at **A** and **B**. By setting the RA′/Dec′ cell position angle $\theta_y = 38°$, the grid dimensions $N_x = 5$, $N_y = 9$, and the map offset $(x, y) = (-6, 0)$, one can map the south-western offset grid starting at $\mathbf{A}_1$. By changing just the map offset to $(x, y) = (6, 0)$, the northern offset map grid can be observed, starting at $\mathbf{B}_1$.

by specifying small maps (`grid`'s) with associated centre offsets, or by observing single points at specific offsets.

1.7 Raster Maps

The definitions of cell and grid are as for grids (above). The telescope motion, however, is continuous along rows in the new x-axis direction. Position-switching to a defined sky-reference is performed at the end of each row.

2 Focus Control and Chopping: the SMU

The subreflector of the JCMT brings radiation to a Cassegrain focus within the receiver cabin through an aperture in the centre of the primary mirror. Proper control of the subreflector is vital to obtaining useful observations at submillimeter wavelengths and is achieved by means of the Secondary Mirror Unit (the 'SMU'), to which the subreflector is attached. The SMU fulfills

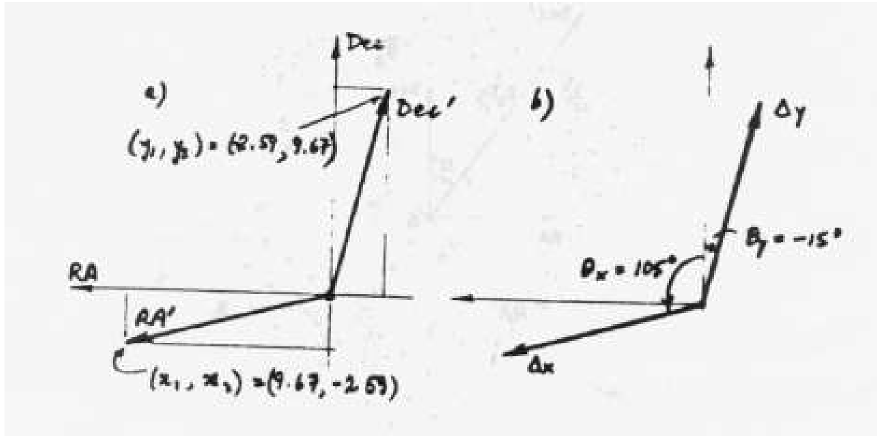


Figure 13: Alternative ways of defining non-orthogonal cells. (a) By providing the coordinates of the ends of the longitude and latitude unit vectors; (b) by defining the angles of the units vectors with respect to the local vertical.

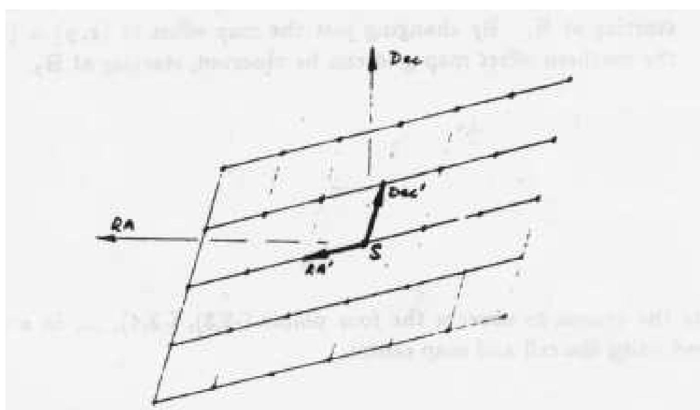


Figure 14: An example of a grid built using the cell definition in Figure 13.

essentially two roles: (1) the elimination to a large degree of the contribution of the atmosphere and the effect of its irregularities from the detected signal, and (2) compensation for deformation of the dish under gravity and temperature. These functions are accomplished by (1) rocking the subreflector fairly rapidly such that the telescope receives the difference in signal between two points on the sky, and (2) modifying the focus in any of three orthogonal directions. Respectively these tasks are performed by mechanically and electronically distinct subsystems of the SMU known in JCMT-talk as the 'chopper' and 'tables'. Observations made with the chopper in operation are referred to as 'chopped', in local parlance.

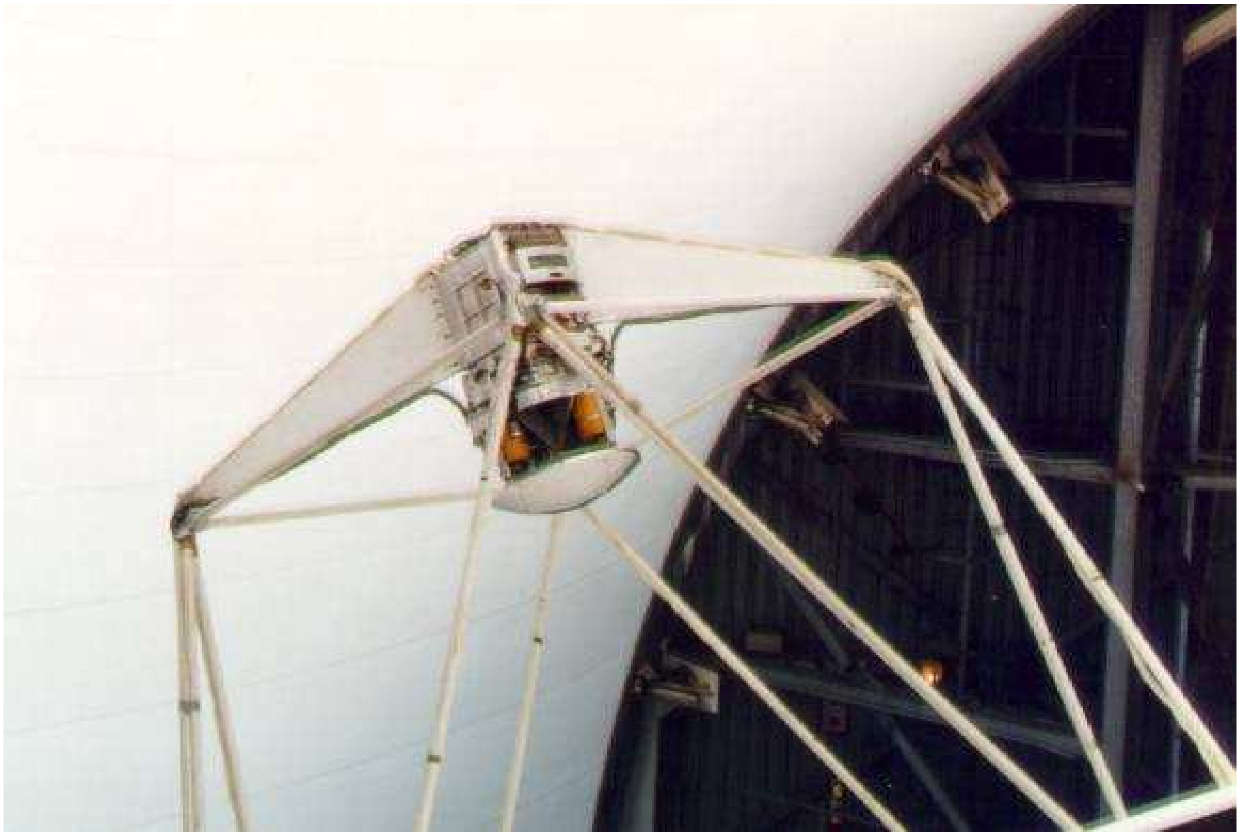


Figure 15: The chopping secondary mirror unit (SMU) is mounted on a carbon-fiber tetrapod and consists of two essential components which allow the mirror to be moved along any of three axes, and rocked ('chopped' or 'nodded') about two axes.

2.1 The SMU Tables

2.1.1 Axes of translation

Translation of the subreflector position to modify the focus plane position is possible in three orthogonal axes: (a) perpendicular to the telescope aperture plane (the z-axis), (b) parallel to the elevation axis (y), and (c) parallel to the telescope aperture plane and perpendicular to elevation axis (x). Thus if the telescope were to be pointed at the horizon, the z-axis then projects horizontally out from the dish surface, x is straight up, and y is from side-to-side.[5] This situation is illustrated in Figure 16. The fact that x and y might appear to be interchanged makes more sense if one imagines the situation when the JCMT is pointed to the zenith. Nevertheless, because there is some ambiguity in defining the coordinates in use, let's leave the telescope at the

[5]The Ancients decreed it thus.

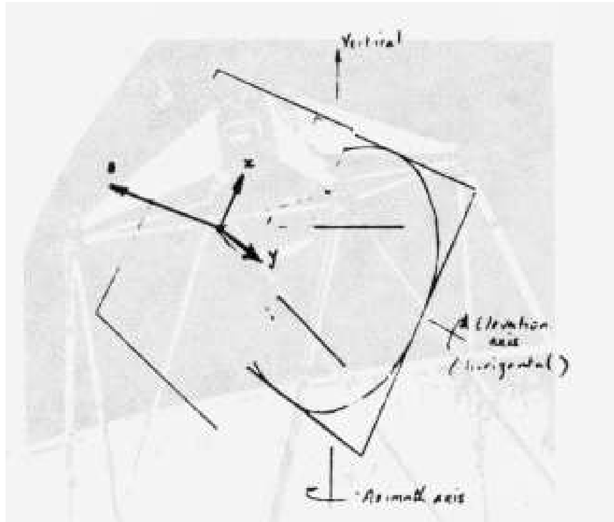


Figure 16: Sketch illustrating the definition of the coordinate axes for the SMU tables (focus) system. The plane with respect to which the axes are defined is parallel to the plane of the antenna.

horizon for the rest of this section (not that the software would allow it!).

2.1.2 Compensating for gravity effects

The homologous deformation design[6] of the JCMT has the elegant property that the surface always deforms under gravity such that it remains a paraboloid at all elevations. The resultant movement of the focus position is highly predictable as a consequence. The necessary compensatory adjustment of the subreflector position in the z (in and out) and x (up and down) directions are modelled in software as a function of elevation, and corrections automatically applied during observing as appropriate (these are known as 'tables updates'). Because of the symmetry inherent in the altazimuth design of the telescope structure, the correction in the y direction (side-to-side) is constant within the measurement errors.

2.1.3 Temperature effects

Over the years it became evident that there is a significant temperature effect on the value of the z-focus position (Z), in the sense that the offset from the idealized homologous deformation value increases with ambient temperature T_{amb}. This effect arises due to temperature changes in the members of the dish backup support structure. Because these small structure components respond quickly to temperature changes, the z-focus must be carefully monitored during the day and for two to three hours after sunset. The relation between T_{amb} and Z is currently [7] set to be

$$dZ = -0.240(\pm 0.016) + 0.058(\pm 0.006)T_{amb}(\mathrm{mm})$$

[6]The general theory of 'homology' is described in von Hoerner, S. (1969), *Structures Technology for Large Radio and Radar Telescope Systems*, eds. J.W. Mar and H. Liebowitz, Cambridge, Mass.; MIT Press, p. 311

[7]see http://www.jach.hawaii.edu/JCMT/telescope/SMU/smu_par.html

There is presently no documented effect of temperature on either the x or y focus values.

The focus behaviour with temperature should be essentially the same for all receivers; however all foci require different offsets for each receiver. Recent values are tabulated as, eg, RXA3I_X_OFFSET in

http://www.jach.hawaii.edu/JCMT/telescope/SMU/smu_par.html

2.1.4 Focus Corrections and Offsets in the JCMT Control System

The focus models and the input of focus corrections are handled by the `SMU` task in the JCMT control system. It is possible to inspect and modify a large number of variables either through ICL or in the more important cases through the SMS menu interface. See *MTUN104*[8] for a complete software description.

The complete focus value consists of three terms; the value according to the current model, an offset which depends on the receiver in use and the precise conditions at the time, and an offset to facilitate focus-switching. The latter is rarely used. Thus for the z-focus, for example, the total focus value is $Z' = Z + DZ + SZ$. The value of Z' (and X' and Y') will be recorded on the operator's status screen, and continuously updated as necessary.

As noted above the values of X and Z are functions of elevation, while Y is constant. Hence:

$$\begin{aligned} X &= x_b + x_a \cos(E) \\ Y &= y_b \\ Z &= z_b + z_a \sin(E) \end{aligned}$$

where, at present,

$$\begin{aligned} x_a &= 5.42 \\ x_b &= -3.98 \\ y_b &= 5.26 \\ z_a &= 1.89 \\ z_b &= -13.52 \end{aligned}$$

DZ (and DX, and DY) are derived from focus fits, and are usually adopted automatically following such fits by the operator. D-offsets may also be inserted 'by hand'. However, *beware!*, because they are cumulative; *i.e.* inserting a D-offset does not replace the existing one, but rather adds to it.

S-offsets are used on the rare occasion that it is felt useful to modulate the focus. This might be done in Z to attempt to eliminate standing waves caused by reflections from the secondary mirror. There are facilities, such as the user-switch procedures, which can be used to define focus-switching. These will be described elsewhere.

2.2 The Chopper

By tilting the secondary mirror the beam of the JCMT may be directed to any point on the sky within about $15'$ of the current coordinates. Modulating this tilt several times per second is

[8] Oliveira, F.J.; *SMU – The Secondary Mirror D Task*

what we call ‘chopping’. The secondary mirror is displaced by actuators controlled via the SMU chopper microcomputer system, which receives commands from the JCMT control system residing in the VAX. Because there are two independent and orthogonal directions in which the secondary can be tilted, a suitable combination of commands to the SMU micros can yield an infinite range of possible chop configurations. In practice, the number of operational configurations used is much more limited; these will be described below. Because there is potential confusion about the chopper axes, it is useful to introduce this topic first, however.

2.2.1 Chopper Axes

The two independent chopper directions are conventionally described for local purposes as ‘East-West’ and ‘North-South’, or alternatively ‘azimuth’ and ‘elevation’ respectively. This terminology makes clear sense only in certain cases, but it is necessary to understand it so that the observer and operator can communicate without error. To picture the situation once again, imagine the JCMT is pointed at the horizon. Then a sideways tilt of the subreflector will cause a deflection of the telescope beam in *azimuth*, while an up-down tilt results in an *elevation* displacement of the beam. This will be almost (but not quite[9]) true for almost any antenna elevation. At the zenith, however, the same motions of the subreflector will produce *East-West* and *North-South* beam displacements *only if the antenna azimuth is 0 or 180°*, *i.e.* aligned directly North or South. Both nomenclatures are fraught with pitfalls, but it is difficult to obtain a better description. It would be preferable to call the axes x and y, except that the more natural arrangement would be the inverse of that used for the SMU tables and seems likely to cause additional confusion. The terminology ‘azimuth’ and ‘elevation’ will be used from now on, as representing the least of the possible evils.

2.2.2 Right, Left and Middle Beam; Beamswitching

From the point of view of the user, the function of the chopper system is best described in terms of the beam positions on the sky. During chopping the telescope beam spends equal times on two positions on the sky, separated by the *chop throw*. As shown in Figure 17, one of these beams is directed at the point of interest (the signal beam `Sig`), and the other is on a reference position `Ref`. Synchronous detection (at the chop rate) of the voltage difference between signal and reference positions yields a result proportional to the source intensity. For most observations the telescope is pointed at the position mid-way between the signal and reference beams, towards `T`, and the two beams defined as above; this minimizes coma lobe distortion and equalizes the contributions to each from telescope scattering and spillover.

For purposes of distinguishing between them, one of these beams is called the ‘right’ beam, and the other the ‘left’. Which is which will be told later! Figure 18 shows the two parts (phases) of a cycle of a ’beam-switched’ measurement. In the first phase (a), the chopper detects the difference between source and sky, with the source in the right beam. In the second phase (b) the telescope is moved by a distance equal to the chop throw to place the source in the left beam, and the resultant detected signal should be the inverse of that obtained in the first phase. After a suitable number of repetitions of these phases the observation finishes. The effect of this method is to eliminate to a large extent not just the sky background (very large relative to the source usually)

[9] The actual resulting beam deflections on the sky are in the tangent plane; an ‘azimuth’ or ‘East-West’ chopper shift will not result in a pure azimuth beam displacement. The difference is usually – except near the zenith – too small to be important, however.

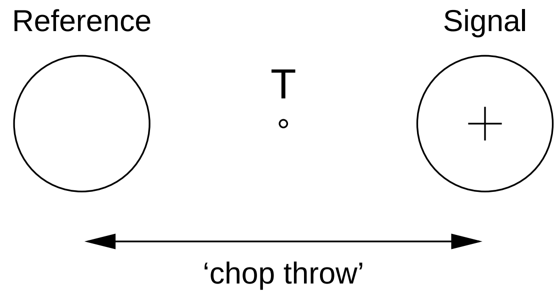


Figure 17: The relative positions of the signal `Sig` and reference `Ref` beam positions, and the telescope coordinate `T` during a chopped observation. The source position is at `+`.

but also its first derivative. This is called *beamswitching* for obvious reasons. Beamswitching thus inherently also involves chopping.

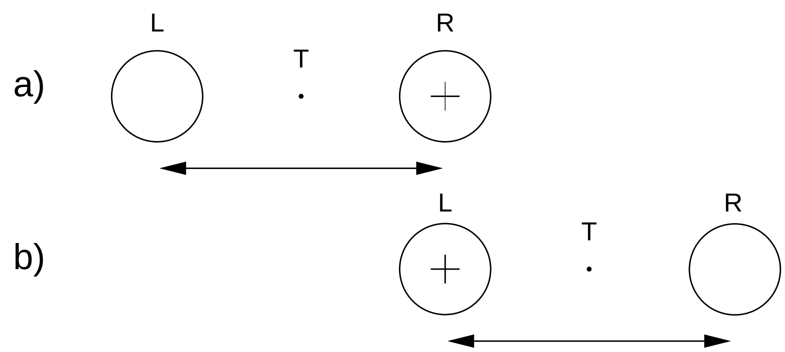


Figure 18: The mechanism of beamswitching. In phase (a) the source is placed in the right beam (`R`), and chopped against (possibly) blank sky in the left beam (`L`). Phase (b) puts the source in the left beam, and chops against a different piece of (supposedly) blank sky in the right beam.

It is normal practice at the JCMT to reverse the sequence of chopping on alternate cycles in order to make the process more efficient. The sequence in which the source is moved from one beam to the other (so-called 'cycle reversal') in this case is

```
R L L R R L L R ....
```

If cycle reversal is turned off, we get the sequence

```
R L R L R L R L ....
```

which is clearly less efficient in its use of telescope time.

A source may also be placed in the 'middle' beam; in this case the telescope will be pointed directly at the source *i.e.* the source at `+` and `T` will coincide, as shown in Figure 19.

If one now chops between left and right beams, in general the source will not be seen. This may not sound terribly useful, and it is not for normal photometric observations; however, if the

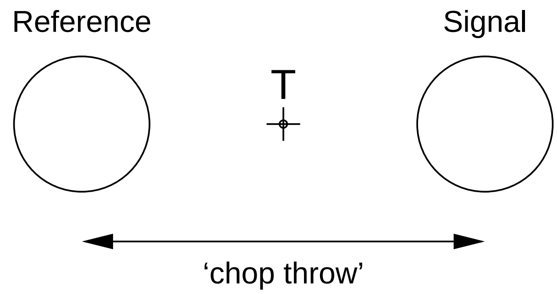


Figure 19: 'Middle-beam' chopping. The right and left beams are symmetrically placed about the source position.

telescope is made to scan ('raster' mode) through the source position while chopping, positive and negative source images will be seen symmetrically placed about the scan centre, and separated by the chop throw. An example of a raster map is given in Figure 20.

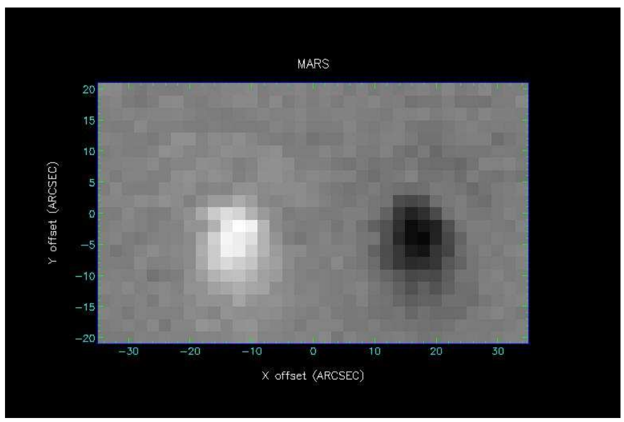
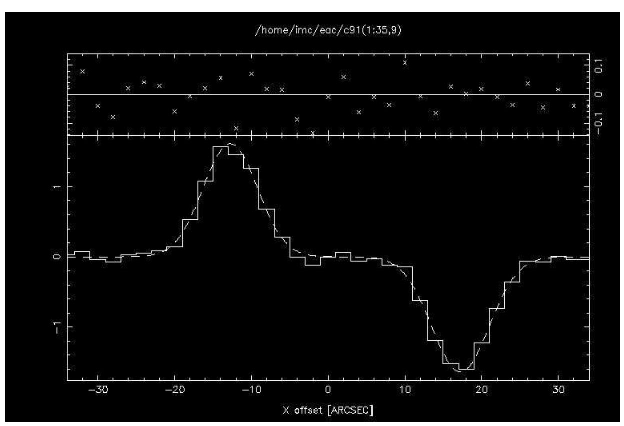


Figure 20: A raster scan through a source using the 'middle' beam (the pointing is obviously awry in elevation). A scan through the centre of the +ve and -ve peaks is shown below:



2.2.3 Chopper Coordinate Frames

In addition to specifying the chop throw and rate one needs to consider both the coordinate frame and position angle of the chop with reference to that frame. The two chopper axes act in concert to produce a chop throw of the requested amplitude along the specified direction.

Two coordinate frames are of interest to the user:

- Horizon altazimuth coordinates (operator selects `AZ`). This is the default, and may be used in combination with any definition of the basic source coordinate cell. This chopper mode is used for most pointing measurements.

- Local coordinates (`LO`). In this case the chopper coordinate frame is the *same as that defined by the coordinate cell command*. The most common case is RA/Dec. This permits the user to chop at an a constant angle *with respect to the source coordinate frame*.

One must also specify the position angle (‘`posang`’) with respect to the chopper coordinate frame in use. For complete command of this activity one needs to know where the right and left beams are on the sky in common cases for different position angles. Careful investigation revealed that the position angle is defined with respect to the local positive-going vertical of the chopper coordinate frame such that a position angle of 90° places the right beam at a *positive* local longitude offset. To illustrate what this means, consider the two common cases:

(a) Altazimuth chopper frame.
For a position angle of 90° (the default) the right beam is offset towards higher azimuth, and for 0° position angle the right beam is offset toward higher elevation. These and other cases are sketched in Figure 21

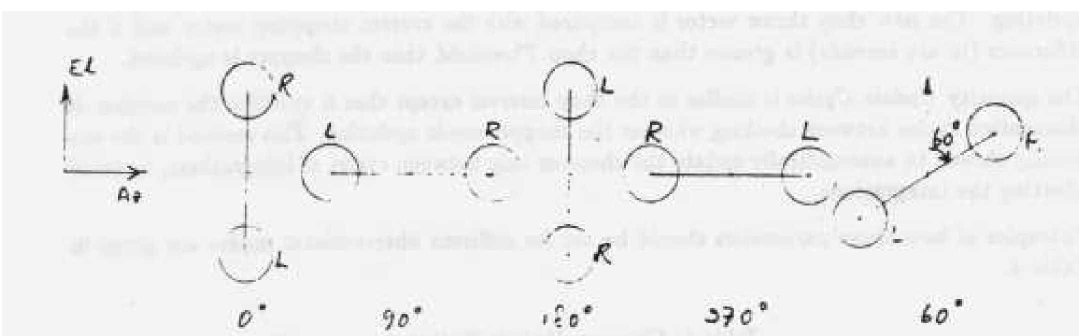


Figure 21: Examples of the relative placement of right `R` and left `L` beams in an altazimuth chop frame, for position angles of 0, 90, 180, 270 and 60°.

(b) RA/Dec (local) chopper frame.
For a position angle of 90° (the default) the right beam is offset towards higher Right Ascension, and for 0° position angle the right beam is offset toward higher declination. Examples are given in Figure 22.

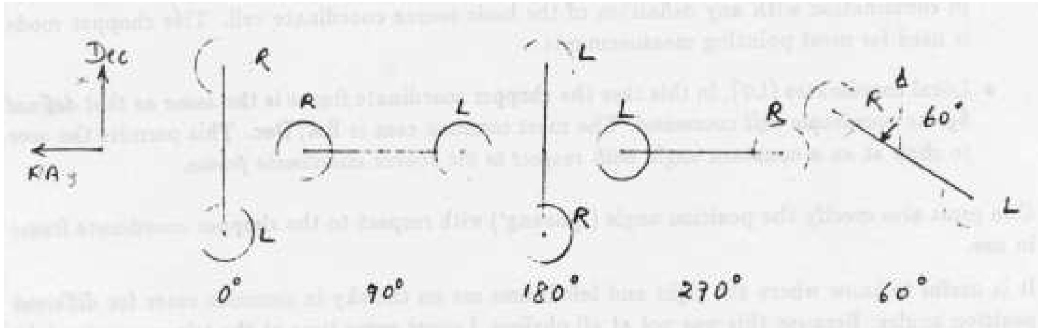


Figure 22: Examples of the relative placement of right R and left L beams in a (local) RA/Dec chop frame, for position angles of 0, 90, 180, 270 and 60°.

2.2.4 Chop Interval, Chop Threshold and Update Cycles

This and the next two subsections have been adapted from *MTUN121*.[10]

If one is using a chopper coordinate frame which rotates with respect to the telescope (*i.e.* anything but AZ), it is necessary to update the *EW* and *NS* chop amplitudes periodically to maintain the same chop direction in the sky frame. Some cases merit more frequent updating than others, and some require inhibiting the updates altogether.

The *Chop_Interval* is the time in seconds at which you want to check the chop coordinates for updating. The new chop throw vector is compared with the current chopping vector and if the difference (in arc seconds) is greater than the *Chop_Threshold*, then the chopper is updated.

The quantity *Update_Cycles* is similar to the chop interval except that it specifies the number of observation cycles between checking whether the chopper needs updating. This method is the one usually chosen to automatically update the chopper only between cycles of integrations, to avoid affecting the integrations.

Examples of how these parameters should be set for different observational modes are given in Table 2.

Table 2: Chopper Update Settings

Observing mode	Any	Normal observing	'Raster'
Cell definition	Any	Any except AZ	Any except AZ
Chop coord system	AZ	LO	LO
Chop interval (s)	0	30	0
Chop threshold ($''$)	1	1	1
Update in cycles	0	0	1

[10]Oliveira, F.J., *New SMU Chopper Software* (1990).

2.2.5 Centre and Circle Chopping

Centre chopping was available previously as 'three beam chopping' and provides arguably better cancellation of sky noise under certain conditions. This mode will switch the observations between left, middle and right beams in the sequence

`L M R M L M R M ...`

In *Circle* chopping the chopper is moved in a circle pattern by generating a sine wave on the *EW* axis and a cosine wave on the *NS* axis; the phase offset for each axis is the position angle of the chop, and the rotation rate of the chopping vector is the chop frequency. The generating functions are:

$$EW = -0.5 * Throw * \sin(Freq * t + Posang)$$

$$NS = -0.5 * Throw * \cos(Freq * t + Posang)$$

2.2.6 External Sync and External Reference Modes

Normally the chopper is driven by its own internally-generated signal. There are however occasions when this is not appropriate.

External Sync mode will allow an external device *e.g.* receiver G, to control the chopper. The operator must set the parameter `EXT_SYNC` to true (= `YES`), and since in this mode the chop frequency is defined by the external device any reasonable chop frequency can be entered without effect.

External Reference mode is a means for an external device to specify the chop throw as well as the chop frequency. This mode is also initiated by setting `EXT_REF` to `YES`.

2.2.7 Practical Chopper Configurations and Observing Modes.

For most applications we use one of two modes; a relatively fast chop cycle at 7.8125 Hz (sometimes 4 Hz) for continuum (bolometer and heterodyne receiver) observations, and a slow chop at 1 Hz for spectral line. Both types of observations are normally beamswitched, so that half of the time the source sits in one beam, and the other half in the other beam. Good sky cancellation is the result. Typically we use chop throws of 60″; sometimes, particularly for making 'raster' maps at the shorter wavelengths we may use a shorter chop throw of say 40″ or less. The observing modes which involve the use of the chopper which we use commonly are: (a) photometry, (b) 'raster' mapping, and (c) beamswitched spectral line.