Chapter 7

On-The-Fly

Based on the OTF manual by Dirk Muders - v1.1 (11-1999).

7.1 On-The-Fly Basics

Traditionally, spectral line maps are observed in a raster mode, switching the telescope between reference and source positions for each individual raster point. This method is very inefficient because of the overhead introduced by initializations and telescope movement. At the SMT the overhead per subscan is on the order of 10 seconds. For a typical 5×5 map integrating 20 seconds "On" and 20 seconds "Off" (i.e. a total of 1000 seconds) the overhead amounts to 2 (On+Off) $\times 5 \times 5 \times 10 = 500$ extra seconds. Thus, the efficiency is only about 66%.

In "On-The-Fly" (OTF) mode, the telescope continuously scans along a row or column with a given velocity instead of tracking the individual raster points. Spectra are written every couple of arc-seconds which corresponds to typical integration times of a few seconds or less (in the future (new AOS control) down to 100 milliseconds). These portions of data are called "OTF dumps".

OTF is more efficient because the telescope system is not initialized for each point along the scanning axis. For the above map it would save 40 subscans or 400 seconds and the efficiency would go up to about 91% ! In addition, one can also reduce the time spent on the "Off" position since OTF is essentially a "several On's per Off" mode. The "Off" time needs to be only $\mathsf{t_{On}}\sqrt{\mathsf{n}}$ where $\mathsf{t_{On}}$ is the time per OTF dump, and n is the number of Nyquist-spaced positions along the scanning axis. Since large regions are mapped rapidly, weather effects are minimized. Thus the final result is more reliable.

Therefore, it is recommended to use OTF whenever mapping a region larger than a few beams in size. There should not be any limitation concerning the line temperatures, although weaker lines require several maps that have to be co-added to reach a sufficiently high signal-to-noise ratio. OTF mapping has the same limits concerning baseline quality as the traditional single-point or raster "On-Off" observations. In the future, we plan to introduce a Wobbler On-The-Fly mode (WMAP) as well as a Frequency-Switching On-The-Fly mode (FMAP; already working at the Effelsberg 100m telescope).

7.2 Setting up OTF Observations

On-The-Fly mapping at the SMT has been implemented via the OBST command "PMAP" which is very similar to the PRASTER verb. The main parameters are as follows (the detailed PMAP syntax is described in appendix 7.4. It is also available in OBST by typing "HELP PMAP"):

PMAP <reflong> <reflat> <refsystem>
/MAPSIZE_PMA <lon> <reslon> <lat> <reslat> <scan direction>
/TIME_PMA <Ton> <Toff>
/ON_OFFS <n on's per off> <f: on first>

PMAP sets up a rectangular raster with one scanning axis (<scan direction>) and one stepped axis perpendicular to the scanning direction. The /MAPSIZE_PMA adverb defines the sizes and steps and the scanning direction which is determined by the keywords "LAM", "BET", "AZM" or "ELV" after the first four /MAPSIZE_PMA parameters. Usually, one uses either "LAM" or "BET" which are equivalent to the two axes of the currently selected coordinate system (e.g. for equatorial LAM $\equiv$ R.A., BET $\equiv$ Dec., for galactic LAM $\equiv l$, BET $\equiv b$). Descriptive coordinate systems with a position angle (e.g. SBAS 1 D)) can also be used and LAM / BET correspond to the new axes.

Figure 7.1 shows a sample PMAP command and the resulting map size and point distribution. It has been centered on (–30″,5″) relative to the source origin using the SET OFFSET command. The scanning occurs along the lambda axis. It is more efficient to scan along the longer edge of the rectangle unless the total time per row or column exceeds the limits set by the stability of the atmosphere (on the order of 10 to 100 seconds depending on weather conditions). The spacing along the scanning axis (the "dump distance") should be a fraction of the beam (here 5″) to avoid smearing. Recent calculations by Beuther (Beuther, Henrik: "On The Fly Kartierung und Multilinienanalyse der interstellaren Molekülwolke Cepheus B". Master's Thesis, Universität zu Köln, 1999) show that half beam spacing leads to about 4% widening while quarter beam spacing results in a beam that is only 1% wider than for raster mapping.

The spacing perpendicular to the scanning axis should be on the order of or smaller than half the beam width to ensure full sampling (here 10″). This map would consist of 12 subscans (6 "Off's" and 6 "On" scan lines). To first explore a large region, one can use a one beam spacing perpendicular to the scanning axis, rather than using a large dump distance which would cause unrecoverable beam smearing.

The "On" time (Ton) is the time per spacing along the scanning axis, also called the "dump time". Currently, the SMT OTF dump time must be 2 seconds or longer because of limitations in the VAX / Camac computer and control system. For the future UNIX / PC / VME system faster dumping (about every 100 milliseconds) is planned to speed up the individual OTF maps in order to minimize atmospheric effects and pointing and possible tracking errors.

The total "On" time per scanning row or column is <Total on time> = <Ton> * <lon> / <reslon> for scanning in LAM and <Total on time> = <Ton> * <lat> / <reslat> for

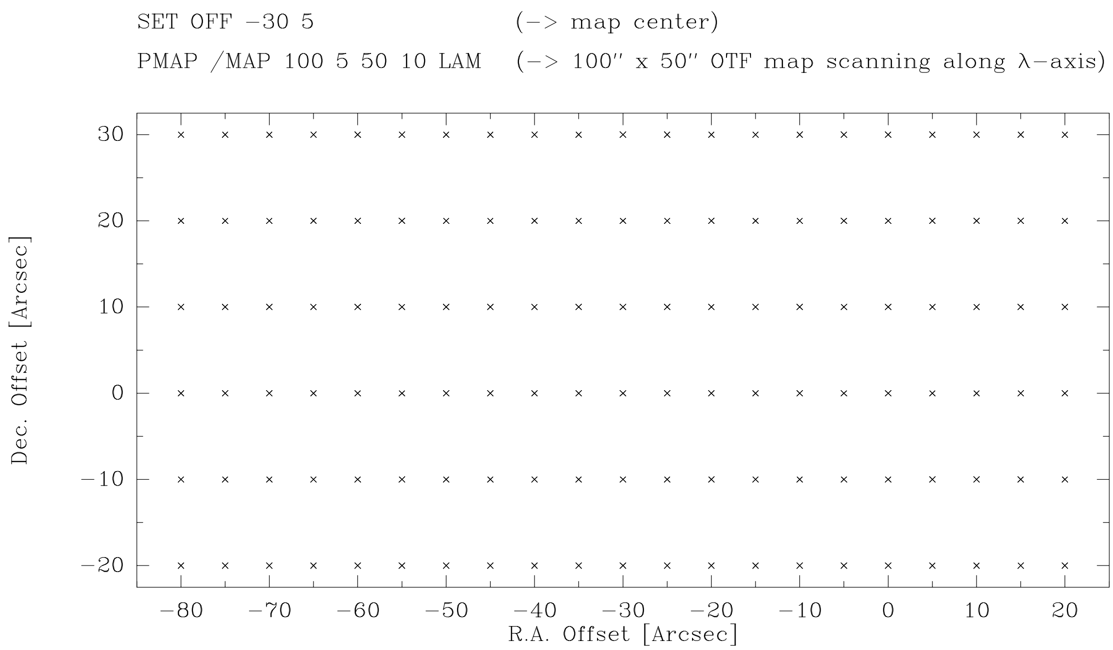

Figure 7.1: Example of an OTF setup in OBST and the resulting map. The map can be centered anywhere relative to the source origin with the SET OFFSET command.

scanning in BET. The time per dump <Ton> should be chosen such that the total time per subscan is on the order of 10 to 100 seconds depending on atmospheric conditions.

The ideal "Off" time would be the total time spent per independent "On" (i.e. all dumps within one beamsize) times the square root of the number of independent "On's" between two "Off's". For example, if you want to scan 150 arc-seconds at 345 GHz (24″ beam) with 8″ dump distance and 2 seconds dump time, you will integrate for $\frac{24''}{8''} \times 2 = 6$ seconds per beam and you will have $\frac{150''}{12.5''} + 1 = 13$ Nyquist-sampled positions. The necessary "Off" time is thus $6 \times \sqrt{13}$ seconds = 21.6 seconds.

The software does not yet know about beam sizes and therefore currently calculates the "Off" time as <Total on time per subscan> × sqrt(<n on's per off>) which is too long. For the time being, you should specify the "Off" time manually using the above formula.

The maximum time for one map (including subscan overheads) should be on the order of 10 to 20 minutes. Then, a new calibration is necessary to compensate for variations in the atmosphere and the receivers and for changes in elevation. One should observe several OTF maps of the same region if the lines are too weak to be detected in one scan. It is also recommended to alternate scanning directions for subsequent OTF maps in order to randomize possible tracking errors (although our tests so far indicate that tracking errors are usually only of the order of a few 0.1″).

7.3 Data Reduction

On-The-Fly mapping produces enormous amounts of CLASS data even at the current slow dump rates. With all 6 backends connected, about 27 kB of data is written every 2 seconds. There is a limit of 100,000 spectra per CLASS file. One should start a new file

(OBST\RENAME command) before reacjing this limit.

The spectra's offset positions are derived from the backend time stamps and represent the actual telescope position at the time of data taking. The positions are calculated for the center of the dump and do **NOT** have to be corrected for zig-zagging.

7.3.1 Online Display

The online display (CHEF running under Solaris) automatically writes a CLASS spectrum for each OTF dump into the SPECTRA.SMT file. A future version of CHEF will write each OTF row or column as one entity (like at the 30m telescope).

Because of the amount of data, the individual spectra are not displayed in the online CHEF window. Instead, a spectrum integrated over the whole scanning axis is shown to provide feedback for the astronomer.

7.3.2 Making Maps

The gridding algorithms that are usually used to make maps of spectral line data employ a simple triangulation scheme. This method works well if the data is sampled on a regular grid like the one that PRASTER produces. However, if the data points are distributed irregularly (like when OTF mapping), the triangulation introduces strong artifacts which make the maps useless. Instead, more advanced schemes like "Gauss × Sinc" weighting or "Orthogonal Convolution" algorithms should be used.

To demonstrate this effect, we have set up a ring shaped test source, added some noise and sampled it on a rectangular grid with some positional jitter (like it occurs in OTF due to variations in the startup time to accelerate the telescope to the scanning speed). We then fed the data into the triangulation command used in the Grenoble Software (GREG2\RANDOM_MAP) and into the Orthogonal Convolution scheme used by the latest Unix version (10/1998) of Robert Zylka's MOPSI (MAP\RANDOM).

Figure 7.2 shows the results of this test. The triangulation (panel b) introduces strong striping artefacts because of the positional jitter and the noise while the Orthogonal Convolution map shows a result close to the expected structure. We strongly recommend to use such an algorithm to grid the OTF data. CLASS has a built-in gridding command called GRID. We have also have MOPSI and there are the gridding tasks GRID_EXTEND and GRID_SG in GRAPHIC. MOPSI is much faster than the other methods, but we recently discovered a problem with shift in the the velocity axis when writing the data from MOPSI to Gildas Data Format (GDF). This bug has NOT yet been fixed ! We therefore recommend using CLASS' GRID to reduce spectral line OTF data.

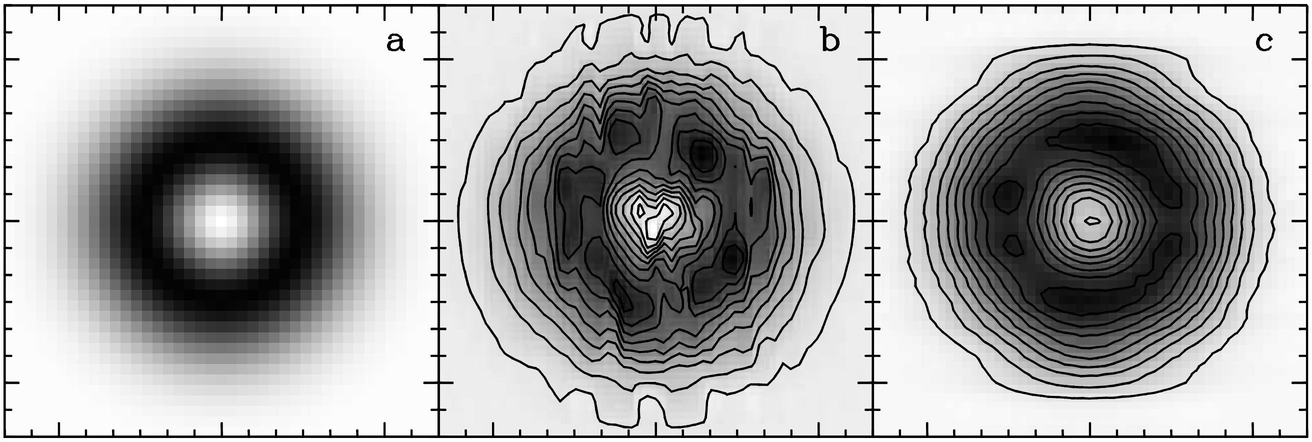

Figure 7.2: Gridding simulated OTF observations of a ring shaped test source (panel a) with the triangulation method (e.g. GREG's RANDOM_MAP, panel b) and with an orthogonal convolution algorithm (e.g. MOPSI, panel c). The triangulation scheme introduces strong artefacts for the OTF data due to the non-square sampling, the noise and the position jitter. The orthogonal convolution algorithm handles the OTF data much better and produces a result close to the original source. It is therefore the preferred OTF gridding algorithm.

7.3.3 CLASS OTF Data Gridding

In CLASS you need to select the source, line, backend and offsets to get a list of observations for the OTF map. Subtract baselines using the BASE command in a FOR NEXT loop and write the spectra to a new output file, e.g.:

```
FIND/ALL
FOR I 1 TO FOUND
   GET NEXT
   BASE 1
   WRITE
NEXT
```

At the SMT site, you can access your data by logging into jever or hannen as user smtobs and using the "spectra" symbol (see note on the monitors in the control room).

After the baseline subtraction, the spectra need to be processed with the ANALYSE\GRID command. It contains a gridding algorithm that can be accessed with the /IMAGE option. It is possible to write all individual channels to get a data cube. The command for this is

GRID <Filename>.gtf NEW /CHANNEL V v_1 v_2/IMAGE BEAM <beam>

where v_1 and v_2 define the velocity interval to be used and "beam" is the beam size in arc-seconds. The filename should have ".gtf" as extension to facilitate reading it in MOPSI (see next section). The above command produces two files: <Filename>.gtf and <Filename>.lmv. The "gtf" (Gildas Data Format) files contain the spectra as binary tables. The "lmv" files contain the gridded cube in Gildas Data Format which can be read with IMAGE in GRAPHIC. They can also be processed with the GRAPHIC imaging tasks (see EXPLAIN in GRAPHIC).

For a quick look at the data while mapping, one can use the "TDV" function which allows to integrate a part of the spectrum and write the area to the "gtf" and "lmv" files.

The syntax for this is

GRID <Filename>.gtf NEW TDV(v_1,v_2)/IMAGE BEAM <beam>

These GRID commands produce data cubes or images with half beam sized pixels. This is quite coarse. One can tell GRID to resample to a smaller pixel size using the LAM and BET options. You need to know the size of the map to correctly specify the arguments. For example, if the map is 240″ × 120 ″ centered on (0″,0″), the GRID command to get e.g. 2″ sized pixels would be

GRID <Filename>.gtf NEW TDV(v_1,v_2)/IMAGE BEAM <beam> LAM 100 1 -120 2 BET 50 1 -60 2

which means that the final map is 100 × 50 pixels large. The second number is the reference pixel, the third is the offset at the reference pixel and the fourth number is the pixel size (all in arc-seconds). Please see HELP GRID in CLASS for a detailed description of these parameters.

The "lmv" data cubes or images can be displayed in GRAPHIC using the IMAGE command. A typical sequence would be

```
IMAGE <Filename>.lmv
LIMITS/RGD
PLOT
BOX/U S
WEDGE
```

You can also use the INPUT and GO BIT or GO MAP procedures to make channel maps of your data (see GREG and GILDAS manuals).

7.3.4 MOPSI OTF Data Gridding

To grid the data with MOPSI [1], one first needs to subtract baselines of all spectra in CLASS and possibly correct for ripples etc. The reduced spectra then need to be written into Gildas Table Format (gtf) using the ANALYSE\GRID command in CLASS (see previous section for details; you can omit the /IMAGE option since only the "gtf" files are needed for MOPSI).

The "GTF" files are read in MOPSI with the command "READ <Filename>.gtf". It will try to read all channels simultaneously. If you run into trouble with memory, you can also specify just a subset of channels using the "PLANE p_1 p_2" option (i.e. the command is "READ <Filename>.gtf PLANE p_1 p_2").

The gridding command in MOPSI is called RANDOM. In its simplest form it accepts two parameters to define the pixel size of the gridded map and another two parameters to define the convolution radii in x and y. A typical command for 345 GHz data would be

RANDOM 2 2/NEI 11 11

which defines a pixel size of 2″ × 2″ and a convolution radius of 11″ (about half the beam size) in each direction.

After gridding the data, the PLOT command can display the channel maps or integrated map (use DEVICE IMAGE BLACK or WHITE to get a display window). Note

[1] Please note that Robert Zylka requests the following acknowledgement in any publication if his software was used for the data reduction: "The data have been reduced with the mapping software package developed by Robert Zylka. This software uses the "restoring" algorithm of Emerson, Klein and Haslam (1979), the "converting" algorithm of Chris Salter (1983), and partly the NOD2 and the GILDAS libraries."

that currently the x axis runs from the left to the right. This is probably a bug in MOPSI and may be corrected later. You can reverse the axis in GREG or GRAPHIC using

LIMITS/RG/REV X.

To go on with the data reduction you can use MOPSI if you are familiar with it (it also contains GREG) or you can write the data to a Gildas Data File (GDF) using the MOPSI command

WRITE <Filename>.gdf

(the ".gdf" extension is necessary to tell MOPSI to write GDF format). The resulting GDF file can then be read e.g. in GRAPHIC for further plotting etc. WARNING: The current version of MOPSI (10/1998) has a bug that causes a velocity shift of a few km/s when writing data cubes to the GDF format. We therefore recommend using the GRID command in CLASS to reduce spectral line OTF maps (see previous section).

7.4 PMAP OBST Help

PMAP

Spectral line On-The-Fly (OTF) On-Off mapping mode. OTF is much more efficient for mapping than the point-by-point modes since it avoids much of the overhead involved in the latter methods. It should always be used for mapping extended sources since the efficiency rises with larger map sizes.

The PMAP command was designed to be very similar to the PRASTER mode. There are, however, a few very important differences about integration times and step sizes. For more information, please read the help on PMAP /TIME_PMA and PMAP /MAPSIZE_PMA carefully !

Syntax:

```
PMAP   <reflong> <reflat> <refsystem>
       /MAPSIZE_PMA <lon> <reslon> <lat> <reslat> <scan direction>
       /TIME_PMA <Ton> <Toff>
       /ON_OFFS <n on's per off> <f: on first>
       /NOOFFSET
```

<reflong>:
Position offset in true angles in longitude for the reference position. Unit is arcseconds.

<reflat>:
Position offset in true angles in latitude for the reference position. Unit is arcseconds.

<refsystem>:
The reference system is specified either in the source coordinate system of the catalogue epoch (possibly rotated if a descriptive system is used):
SOURCE, BASIS, LAMDA, BETA are all equivalent inputs
or in the current horizontal system:
HORIZONTAL, AZIMUTH, ELEVATION are equivalent inputs.

/MAPSIZE_PMA <lon> <reslon> <lat> <reslat> <obs_system>:
Example: /MAPSIZE_PMA 100 5 80 10 LAM

The map is dimensioned 100x80 seconds of arc with a step size of 5 seconds of arc along the scanning axis (LAM) and 10 seconds of arc in the beta direction.

Be careful to choose the step along the scanning axis small enough so that no considerable beam smearing occurs. This step size should be a small fraction of the beam size.

The step size perpendicular to the scanning axis can be chosen freely. For best results it should be smaller than half the beam size. You can, however, later combine several coarsely spaced maps to get a fully sampled final map.

<lon> <reslon>:

<lon> defines the length of a line in the lam-direction and <reslon> the distance between two lines or between rasterpoints.

<lat> <reslat>:

This has the same meaning like <long> <reslon>, but for the beta direction.

<obs_system>:

Chooses the scanning coordinate of the map. Possible values are:

LAM: scans in longitude, latitude is orthogonal axis BET: scans in latitude, longitude is orthogonal axis AZM: the same for azimuth and elevation ELV: the same for elevation and azimuth

/TIME_PMA <Ton> <Toff>:

"Ton" specifies the time per OTF raster point. This is NOT the time per subscan ! A subscan consists of a series of OTF raster points and represents a full row or column of the map.

The total time for one OTF row / column (i.e. one "On" subscan) is Ton*lon/reslon (or Ton*lat/reslat for the other direction).

"Ton" translates into backend dump times. Currently, the minimum value for "Ton" is 2 seconds because of data rate limitations with the Vax / Camac system. Ideally, "Ton" should be between 2 and 6 seconds to get reasonable scanning velocities.

You will get more integration time per beam along the scanning axis because OTF maps are heavily oversampled. To get even more integration time you should repeat the full map several times. It is better to observe several short maps with intermediate calibrations than one long map because changes in the system and the atmosphere will be smaller.

"Toff" specfies the time to be spent on the reference position. If omitted, the reference time is calculated automatically and set to the optimum value of Ton*sqrt(Num of On's per Off).

/ON_OFFS <n on's per off> <f: on first>:

Number of On's per Off. Currently, the map should start with an Off since the reduction software cannot yet handle other setups.

/NOOFFSET:

The ON observation is made at the position of the object specified by SOURCE without any offsets specified by the SET OFFSET command.