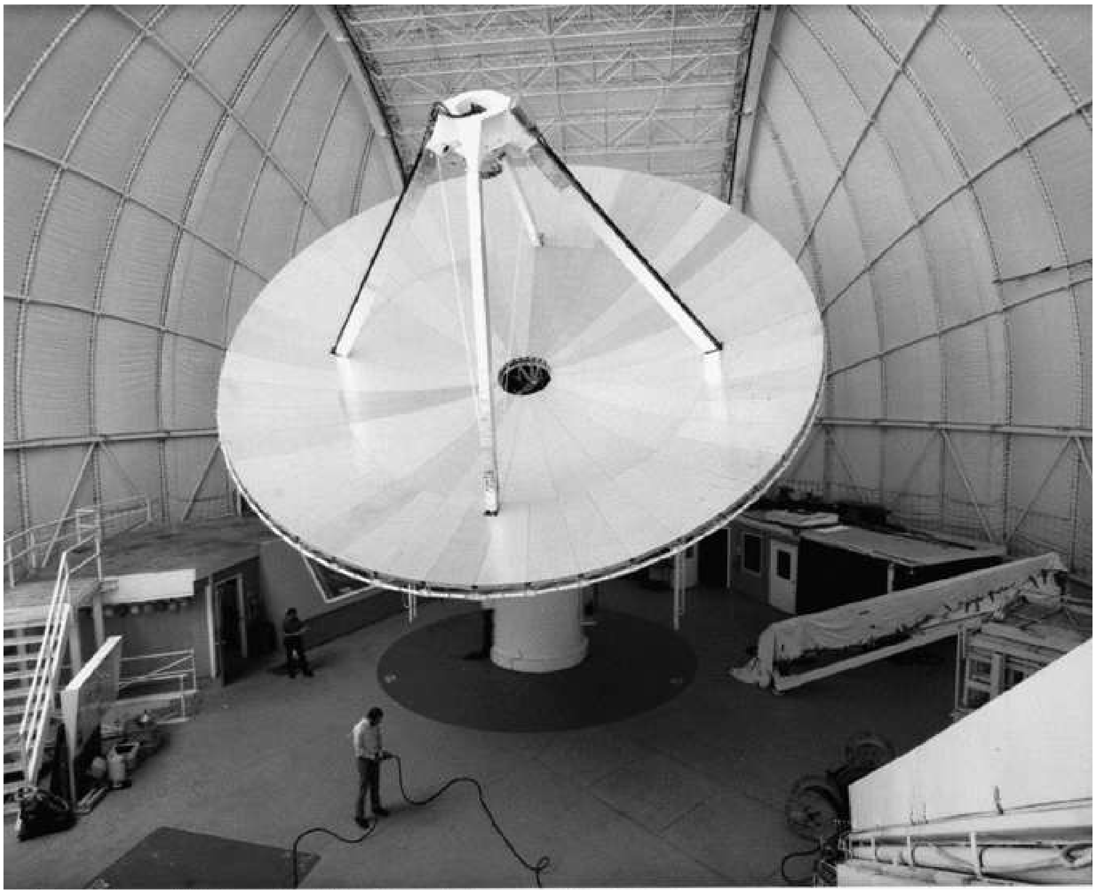

National Radio Astronomy Observatory Tucson, Arizona

User's Manual for the NRAO 12 Meter Millimeter-Wave Telescope

Kitt Peak, Arizona

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Preface

Our intent with this manual is to provide a general reference book for the operation of the NRAO 12m millimeter-wave telescope. We have included basic material required for first-time use of the telescope, as well as more detailed information of possible interest to all observers. In addition to this manual, we recommend that first-time users read the companion document *Visitor's Guide to the NRAO 12m Telescope* before coming to the telescope.

We are sure that there is room for improvement in this manual, and ask users to bring to our attention any errors, omissions, or unclear passages. **Please note that we actively maintain this manual. The most up-to-date version of this document can be found on the NRAO Tucson Home Page at http://www.tuc.nrao.edu/Tucson.html and at the telescope.**

There are a number of companion documents which you should consult for more detailed information regarding On-The-Fly observing, the current equipment and calibration status, and the 1mm Array receiver. The following list itemizes these supplementary documents, most of which are accessible via the NRAO Tucson Home Page.

- *The NRAO 12m Telescope Equipment and Calibration Status*: Information on current equipment characteristics, such as receiver temperatures, telescope efficiencies, *etc.*
- *On The Fly Observing at the 12m Telescope*: On The Fly data acquisition and analysis
- *Visitors' Guide to the NRAO 12m Telescope*: General guide for prospective observers
- *Observing with the NRAO 1mm Array Receiver*: Observers' guide to the 1mm Array receiver

Jeff Mangum

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Chapter 1

Introduction

1.1 The Observatory

The National Radio Astronomy Observatory (NRAO) 12 Meter Telescope is a general purpose radio astronomical observatory that supports spectral line and continuum observations in the atmospheric windows at 3 mm, 2 mm, and 1.2 mm wavelengths. The facility is located on Kitt Peak, Arizona, approximately 50 miles southwest of Tucson. The Observatory was constructed in 1967 with an original surface diameter of 36 feet (11 meters). In 1982, the surface and backup structure were replaced with a 12m diameter reflector. Table 1.1 lists basic information on the observatory site and telescope.

The NRAO operates the telescope as a visitor facility, open to use by competent observers without regard to affiliation or nationality. Proposals are accepted before three deadlines each year and are evaluated by a panel of anonymous referees (see §1.2 for more information on proposal submission). The telescope is open for visitor use from approximately September 15th to July 15th each year. From late July through the middle of September the prevailing weather pattern precludes observations at millimeter wavelengths and the telescope operation is shut down. Extensive overhauls, telescope upgrades and major maintenance are done during the summer shutdown period.

The 12 Meter Telescope is one of five observatory units operated by the NRAO. The NRAO is administered by Associated Universities, Inc. (AUI), under cooperative agreement with the National Science Foundation. Operations of the 12 Meter Telescope are managed by the Assistant Director who, with the Assistant Scientists, also handles the scheduling of the instrument. The Assistant Director or Deputy Assistant Director should be contacted with regard to general matters of operations policy. In addition, more general questions or comments pertaining to Observatory-wide activities (scheduling procedures, scientific or instrumentation priorities, inter-site relations) or specific criticisms of, or suggestions for, the Tucson operation may be addressed to the Director of the NRAO located at the Charlottesville, Virginia office.

Additional visitor information, including maps, lodging fees, travel reimbursement policies, and names of specific staff members responsible for operation of the telescope can be found on the NRAO Tucson Home Page at http://www.tuc.nrao.edu/Tucson.html. This information can also be found in the companion document, *Visitors' Guide to the NRAO*

Table 1.1: Telescope and Site Characteristics

Site		
	East Longitude:	$-111^\circ\ 36'\ 53.''475$
	North Latitude:	$+31^\circ\ 57'\ 12.''0$
	Elevation:	1894.5 meters (6215.8 feet)
Telescope		
	Primary Reflector Diameter:	12.0 meters
	Focal Ratio (f/D)	
	Prime Focus:	0.42
	Cassegrain Focus:	13.8
	Surface Accuracy:	75 μm rms
	Mount:	Elevation over Azimuth
	Slew Rate:	68°/minute
	Pointing Accuracy:	$5''$ rms
	Elevation Limit:	15°
	Enclosure:	Tracking astrodome with movable door

12m Telescope.

1.2 Observing Proposals

1.2.1 Proposal Preparation

All proposals should include a completed 12m Observing Application Cover Sheet. The body of the proposal must include:

1. A concise scientific justification for the project (Do not exceed 1000 words);
2. An estimate of the observing time required;
3. Frequencies and source coordinates to be observed.

As a proposer, you should insure that the project is within the capabilities of the telescope, both in terms of available equipment and the sensitivities and integration times required. The telescope and receiver parameters and system sensitivities given in §3.3 will be of use in estimating the required integration times. The most up-to-date information on these parameters can be found in the companion document *The NRAO 12m Telescope Equipment and Calibration Status* and on the NRAO Tucson Home Page (http://www.tuc.nrao.edu/Tucson.html).

The 12m management imposes no hard rules as to the maximum or minimum lengths of observing programs. A typical 12m observing run lasts 3 or 4 days of either partial or

Table 1.2: Proposal Submission Deadlines

Deadline	Observing Period
January 1	April to mid-July
July 1	mid-September to December 31
October 1	January 1 to March 31

around-the-clock time. Requests for more than 5 days of time usually receive close scrutiny by the referees and scheduling committee. If only a specific LST range is required, you should request only that range.

For any proposal period, the Scheduling Committee always receives more proposals than can be scheduled; the requested time often exceeds the available time by factors of 2 – 4. For this reason, you should prepare proposals with care.

1.2.2 Proposal Submission and Refereeing

Twelve meter telescope scheduling operates on a trimester system, with proposal submission deadlines and their corresponding observing periods listed in Table 1.2. The intention of the 12m proposal system is to insure that the projects granted telescope time are of current interest and that all proposals receive a prompt scheduling decision.

Proposals should be sent to the Director of the NRAO in Charlottesville, Virginia. Information regarding electronic submission of proposals can be found on the NRAO Tucson Home Page (http://www.tuc.nrao.edu/Tucson.html). After receipt by the Director's office, the proposals are assigned a reference number and are sent to a panel of five referees who are anonymous to the proposer and to each other. The referees rank the proposal as to scientific merit and feasibility of achieving the scientific goal, recommend what percentage of the requested observing time should be granted, and make any comments they feel are pertinent. On the basis of the referees' rankings and comments, the 12m Scheduling Committee selects the proposals to be scheduled. A report of referees' comments and the disposition of the proposal is sent to the proposal's contact authors, usually within 6-8 weeks after the deadline.

Proposals are considered for two consecutive trimester periods. On a proposal's second consideration, it will be in competition with new proposals received for that period. If a proposal is not selected on its second consideration, it will be declared inactive and generally will not receive any further consideration for telescope time.

The 12m Scheduling Committee will notify proposers as to the disposition of their active proposals after each selection process. After any evaluation of a proposal, the authors may submit an amended version of the proposal to address referees' remarks or to otherwise strengthen the proposal. The proposal will be re-refereed for the next available period. Investigators are also free to withdraw a proposal and resubmit it as a different proposal.

1.2.3 Proposal and Observing Propriety

Observers are expected to confine their observations to those described in their refereed proposal. It is absolutely essential that observers consult with the Assistant Director or Deputy Assistant Director and obtain his approval before altering scheduled observing programs. Approval for changes can be granted under those circumstances that do not lead to an infringement on work proposed by others, and when the changes are in keeping with the spirit of the original, refereed proposal. These rules are fundamental to the integrity of the observing system at NRAO and are taken very seriously by the management.

1.3 Observatory Policy

1.3.1 Staff Responsibilities

The following is the responsibility of the NRAO staff:

- To insure that the equipment needed for your observations is available and installed at the telescope.
- To tune the receiver to the desired frequency.
- To provide sound telescope pointing.
- To provide fundamental telescope calibration parameters – efficiencies, beamwidths, gain curves – at standard observing frequencies.
- To provide advice on observing strategies, if requested.

1.3.2 Observer's Responsibilities

As the visiting observer, you have the responsibility for proper supervision of all aspects of the observing program. This includes:

- Providing to the NRAO staff, well in advance of the time scheduled, a full description of the equipment needed for the observations as well as a complete list of frequencies to be observed. Usually this information is included on the proposal cover sheet.
- To verify the telescope pointing and fine-tune it as needed.
- To obtain all calibration and other receiver/telescope parameters necessary for data reduction. This can be done either by adopting or scaling the NRAO-provided information from standard frequencies, and/or by making the appropriate measurements. In either case, proper data calibration is your responsibility, not the NRAO's.
- To inform the NRAO staff, before the observing period has ended, about the types of data to be written on an export tape, and the format of the export tape.

In addition, you are requested to provide feedback on the observing run via the "Observer's Comment Sheet", available at the telescope and on the NRAO Tucson Home Page.

1.3.3 Maintenance and Repairs

One period approximately every 10 days is assigned to preventive maintenance and routine system tests. If during a scheduled observing period a catastrophic failure of the instrument occurs which results in a loss of data, observations will be stopped and the NRAO technical staff will attempt to repair the equipment. In less serious cases where data-taking continues but where the quality of the data is not optimal, it is your responsibility to decide whether or not you wish to give up telescope time so that repairs can be made. Only the Tucson Assistant Director can make the decision to interrupt scheduled operations to make non-essential repairs.

1.3.4 Sharing Telescope Facilities with Other Observing Teams

Since living quarters and work spaces at the telescope are limited, you should leave the mountain as soon as possible at the end of your run, allowing, of course, for a reasonable period of rest. If you wish to continue the reduction of your data sets, you should do so at the NRAO Tucson office. When two or more observing teams are sharing observing time, the team currently observing has priority to all telescope facilities, including computer usage. The other observing teams should endeavor to stay out of the control room and not interfere in any way with the ongoing observations. Unless one group of observers is declared the "prime observer" on the telescope schedule, equipment changes needed for a program will be done at the beginning of that program's time.

1.3.5 Observations Under Poor Weather Conditions

There are a variety of weather conditions which can endanger the safety of the telescope. It is the responsibility of the telescope operator to take appropriate action if any of the conditions listed below occur.

1.3.5.1 High Winds

- If the wind exceeds 15 mph, observations will be restricted to those quadrants where the telescope drive motor currents are not excessive.

- If the steady wind, or the average of gusty wind, exceeds 35 mph the dome door must be closed. Observations can be continued through the side of the dome.

- For winds above 45 mph, the dome door must be positioned 180° from the direction of the wind and held fixed. Observations can continue through the side of the dome, but the dome cannot be moved.

- If the wind exceeds 55 mph operations must cease and the telescope must be placed in the service position with the stow pins in place.

1.3.5.2 Moisture Accumulation In or On the Dome

If there is fog in the dome, or if moisture is condensing on the antenna or equipment, the dome door will be closed. Observations can continue through the side of the dome. If there is a build-up of snow/ice on the dome, the accumulated snow/ice must be cleared from the dome door before observations can resume.

1.3.5.3 Sun on the Dish

The pointing and focus of the dish can be seriously affected if the sun is allowed to shine on the surface of the dish or the feed support legs. If accurate pointing is desired, care must be taken to keep the sun off the dish. To avoid excessive heating of the feed legs, the prime focus regions, and the cables to the prime focus, the dish will not be pointed to within 15 degrees of the sun. The projected distance between the sun and a position on the sky defined as (AZ_{obj},EL_{obj}) is given by the following equation:

$$\cos(D_{obj}) = \cos(90-EL_{\odot})\cos(90-EL_{obj})+\sin(90-EL_{\odot})\sin(90-EL_{obj})\cos(AZ_{obj}-AZ_{\odot}) \tag{1.1}$$

1.3.5.4 Observations Using Emergency Power Generators

The telescope and dome have three sources of electric power – the commercial source and two power generators. Observations can continue as long as at least two of the sources are operational. If only one source of power is available, the dome door must be closed.

1.3.5.5 Safety Rules

The following safety rules obtain at the 12 Meter Telescope site. We expect all observers and visitors to the site to read and abide by these rules.

1. To drive a GSA car, you must possess a valid driver's license.

2. The Telescope Operator on duty is the only person allowed to operate the telescope.

3. Observers are not to be on the telescope unless the duty operator has specifically authorized them to be there.

4. Safety chains and rails have been installed at the entrance to the observing rooms. They are there to prevent you from walking into any possible pinch points or dangerous areas.

5. Do not stand in the red areas because parts of the telescope and dome that move in those areas could injure you severely.

6. Do not touch the yellow curtains around the inside wall of the dome. Behind them are exposed 480-volt power lines.

7. Please abide by all printed and posted safety rules such as “No Smoking” and “Do Not Enter This Area” posters, etc.

8. Only the telescope operator or other qualified Arizona employees are allowed to operate the “cherry picker”. Observers may ride in the cherry picker if authorized to do so by the duty operator.

9. Hard hats are required for all persons in the dome area if someone is working above or in the cherry picker. The hats are located on the wall just outside of the observing room door.

10. When walking outside to the dormitories or the lab at night, please be sure to carry a flashlight. You may encounter steps, drop-offs, or hungry wild animals.

11. The consumption of alcoholic beverages or illegal drugs is absolutely forbidden in the lab and telescope/control room areas.

12. All employees and observers are required to wear seat belts while riding in government vehicles.

13. Ice, rocks, and rock slides are frequently a hazard on the roads and walkways. Cattle and horses cross Highway 386 and several have been hit. Please drive and walk carefully.

14. Please drive very slowly and carefully in all NOAO and NRAO parking or road areas. Pedestrians, including small children seem to leap out at cars on a regular basis.

15. A more complete list of safety rules and recommendations is available in the observers' lounge and from the telescope operator. You might find it interesting reading, although not required.

Chapter 2

Getting Started

2.1 What to Bring to the Telescope

Your observations will be more efficient and you will achieve better results if you have thoroughly prepared for your observing run before arriving at the telescope. Most of this work should be done at the time the proposal is written (see Chapter 1). For both spectral line and continuum observations, you should prepare the following before coming to the telescope:

Source List: A source list with epoch B1950 or J2000 RA and Dec or (lII, bII) Galactic coordinates. For spectral line observations you will also need the source velocities in the LSR, optical, or relativistic velocity reference frames (see Chapter 4). Keep in mind that the beam sizes for the 12m can be quite small ($\sim 20''$) at the higher frequencies so the positions should be appropriately accurate. You can save time by composing your catalog prior to your observing run. See Chapter 4 for the source catalog format.

Line Rest Frequencies: You should have line rest frequencies which are accurate to at least 10 kHz. If emission lines are weak, test line frequencies should be included. For continuum measurements, choose your observing frequencies so that no strong spectral lines lie in either of the receiver sidebands.

Observing Mode: The available observing modes for spectral line observations are

- Total Power Measurements
- Relative and Absolute Position Switching
- Frequency Switching
- Beam Switching
- Grid Mapping
- On-The-Fly Mapping

while the available observing modes for continuum observations are

- Switched or Total Power ON/OFF's
- Grid Mapping
- On-The-Fly Mapping

Reference Positions: The reference offset position, in angle or frequency, should also be considered carefully. If you are using beam switching, you should consider carefully the optimum beam separation. The default beam throws are $\pm 2'$ at 3 and 2mm wavelengths, and $\pm 1'$ at 1mm wavelengths.

Spectrometer Configuration: For spectral line observations you need to determine how you will configure the filter banks and Millimeter Autocorrelator (MAC), including the resolution and the mode of operation. This decision hinges on the resolution and total bandwidth required. No firm rules exist, but the minimum resolution acceptable should probably give 3 – 5 channels across the line and the minimum bandwidth should have 10 – 20% of the band on each side of the line.

2.2 Startup Checklist

A general startup checklist for both spectral line and continuum observations is given below. Although the Observatory staff tries to provide a fully functional system and advice about calibration constants and procedures, the responsibility for the integrity of the data rests with the observer. This checklist will help insure that the system is configured properly and that variable quantities such as pointing and focus are properly set. Completion of this checklist may take an hour or more, but the time will be well-spent.

1. Have the operator tune the receiver to the desired frequency, including sideband and harmonic checks.

2. Select a strong continuum source from the list of standard sources (see Chapter 4). A bright planet (*i.e.*, Venus, Mars, Saturn, or Jupiter) is preferable. Pick one whose position is near the first program source, if possible.

3. Ask the operator to perform a five-point map of the source to check for pointing offsets. Records of recent pointing offsets are kept on graphs near the observer's console and can be used to estimate an initial value for the pointing. The operator will need to know the map grid spacing (the default value is $\frac{1}{2}$ the beam FWHM) and the integration time per point. A detailed discussion of telescope pointing characteristics is given in Chapter 4. When the five-point measurement is complete, a fit will be made to the measurement on-line and displayed on the on-line data server. You can also reduce these measurements by hand using *UniPOPS* (see §2.3). If the fit to the five-point is poor, repeat the measurement with updated pointing.

4. Ask the operator to perform a *focalize* on the chosen continuum source. This checks for the best value of the axial focus. The focalize measurement requires that you specify a first guess for the focus position (called F0) and the spacing between the

focus settings (called WL). The system will automatically set F0 to a reasonable starting value (usually around 45 mm). WL is usually chosen to be $\frac{1}{2}$ the observing wavelength. When the focalize measurement is complete, a fit will be made to the measurement on-line and displayed on the on-line dataserver. You can also reduce these measurements with the *condar* analysis program. See Chapter 4 for more focus information and §2.3 for data reduction commands. If the fit to the *focalize* is poor, repeat the observation with an updated value for F0.

NOTE: Pointing and focus may change as the temperature of the dish (or parts of the dish) changes. Pointing and focus should be checked (at least) after nightfall and daybreak and more frequently if the dish is illuminated by the sun.

5. For spectral line observations, you should perform the following checks to insure that the receiver is tuned correctly, the spectrometer is properly configured, and the calibration scale is correct.

   (a) If the program line is weak and no other strong lines are in the bandpass, tune first to a strong test line that is as close by in frequency as possible. "Strong" means any line that will produce a good signal-to-noise spectrum in a 5 – 10 minute integration, for example. Standard sources are listed in the NRAO standard catalog (called "standard.cat"). If possible, use the same observing setup (same spectrometer mode and observing mode) as will be used for the program observations. If the observations are of a common species, such as CO, there is no need to tune to another line.

   (b) Perform a calibration scan and check for bad channels in the filter banks. Report the bad channels to the operator, who will flag those channels in the control system software.

   (c) Observe a test line in a strong source. Observers may wish to verify the sense of the velocity/frequency scale by shifting the rest frequency or center velocity by a small amount and seeing if the line moves in the correct direction for the sideband choice.

   (d) Check that the line temperature calibration is correct. This can be done by observing a standard source, presuming that the test line has known strength. Measurements of many of the sources in the NRAO standard catalog "standard.cat" have been made in the CO, ^{13}CO, and C^{18}O J $= 1 \rightarrow 0$ and J $= 2 \rightarrow 1$ transitions. Plots of these spectra can be found at the telescope and on the NRAO Tucson Home Page.

2.3 Basic Data Reduction with UniPOPS

Two other manuals, one for spectral line and one for continuum, describe the data reduction systems in use at the 12m. These are available at the telescope and upon request. The discussion below is intended only as a quick reference list to help the observer get started.

Raw data is accumulated into two data files; one which contains filter bank data and a second which contains Millimeter Autocorrelator (MAC) data. Both of these files are in the

Table 2.1: Subscan Codes For 12m Data

Subscan	Configuration
Filter Banks	
01	IF1 in filter bank 1 (series) or first half of filter bank 1 (parallel)
02	IF1 in second half of filter bank 1 (parallel)
03	IF2 in filter bank 2 (series) or first half of filter bank 2 (parallel)
04	IF2 in second half of filter bank 2 (parallel)
Millimeter Autocorrelator	
11, 12, ..., 18	IF1, IF2, ..., IF8 for 1mm Array observations
11	IF1 in 2IF mode or IF1 at frequency 1 in 4IF mode
12	IF2 in 2IF mode or IF1 at frequency 2 in 4IF mode
13	IF2 at frequency 1 in 4IF mode
14	IF2 at frequency 2 in 4IF mode
Single-Beam Continuum	
01	IF1
02	IF2
1mm Array Continuum	
01, 02, ..., 08	IF1, IF2, ..., IF8

"sdd" or Single Dish Data format. Each of these files has an associated gains, or "gsdd", file which contains results for spectral line calibration scans. In the following we give a brief introduction to the analysis of the spectral line and continuum data accumulated into these data files.

Before observations begin, the operator will set up a subdirectory containing data files. This subdirectory is private to each observing team, and is denoted by `/obs/ini`, where `ini` are the 3 letter initials of the lead observer. The data files in this subdirectory are also labeled with the same initials. Log into the system as username `obs` (the operator can tell you the current password for this account). You will then be prompted for your initials, discussed above. After the login process is complete, you will be in your `/obs/ini` subdirectory.

The spectral line system always records data from two 256 channel filter banks and up to 65536 channels from the Millimeter Autocorrelator (MAC). Each scan is composed of a number of subscans/indexdata!subscan which individually contain one filter bank or Millimeter Autocorrelator (MAC) measurement. Table 2.1 lists the subscan codes with their associated polarizations and backends.

To start the continuum analysis program from the Unix prompt, type

```
condar
```

while to start the spectral line analysis program at the Unix prompt, type

```
line
```

Table 2.2 lists a number of *condar* and *line* commands and their function, while Table 2.3 lists a number of basic data analysis procedures.

2.4 Alternate Data Analysis Packages

There are a number of other data analysis packages available at the 12m which can be used to analyze 12m data. All of these packages require a conversion of the 12m sdd-format to the resident format of the analysis package to be used. Below I describe the most popular alternate analysis packages in use at the 12m.

2.4.1 CLASS

Conversion of sdd-format data to *CLASS* format is currently done on-line. All scans except continuum and OTF measurements are automatically converted to CLASS format and put in a file called *class.12m* in the observer's directory. One can also convert other sdd-format data files to *CLASS* format using a utility program called *uni2class*. To convert all data in the sdd file sdd.jgm_001, issue the following command from any Unix prompt on any of the mountain workstations:

```
uni2class /home/data/jgm/sdd.jgm_001 sdd.jgm_001.class
```

for the filter bank data and

```
uni2class /home/data/jgm/sdd_hc.jgm_001 sdd_hc.jgm_001.class
```

for the Millimeter Autocorrelator (MAC) data. The second parameter in *uni2class* is the output file name. The current features and limitations of this conversion are:

- Each spectrum is assigned a unique observation number in the *CLASS* file according to the perscription described in Table 2.4. For filter bank data, the nomenclature used for the *CLASS* telescope field identifier is "FB" for filterbank followed by a two-number identifier indicating which filter bank (there can be only two) and which polarization from a filter bank this scan represents. For Millimeter Autocorrelator (MAC) data, the nomenclature used is "MAC" followed by a two-number identifier indicating which rest frequency (there can be two) and which polarization from a given frequency this scan represents. *CLASS* does not support subscan numbers. The original scan number is preserved in the header.

- The *UniPOPS* backend descriptor is converted to a more useful identifier which is inserted into the *CLASS* telescope field to avoid ambiguities between subscans for a particular scan.

- Map offsets are carried over. There seem to be small ($<1''$) discrepancies in times and coordinates between the sdd and *CLASS* files which are perhaps due to roundoff error.

Table 2.2: Analysis Commands in UniPOPS

Command	Function
Commands Common to Both *condar* and *line*	
get scan_number.nn	Retrieves scan_number.nn into the work area.
xx	Alias for "page show", which plots scan_number.nn following a "get".
header	Displays the header from scan_number following a "get".
scan_number add	Adds scan_number to the stack.
beg_scan end_scan add	Adds all of the scans between beg_scan and end_scan to the stack.
c#	Averages all of the scans in the stack and displays the average for channel # (where # is 1 or 2).
cb	Averages all of the scans in the stack and displays the average for channels 1 and 2 combined.
tell stack	Lists scans in the stack.
empty	Empties the stack.
yrange(ymin,ymax)	Sets the vertical scale to the range ymin to ymax.
freey	Resets automatic scaling for the y-axis.
Commands Specific to *condar*	
scan_number.nn s	Gets and displays the continuum ON/OFF sequence scan_number.nn.
scan_number.nn s ave	Gets, displays, and prints the average and rms flux of the continuum ON/OFF sequence scan_number.xx
scan_number.nn f	Analyzes and plots a five-point map of scan_number.nn
scan_number.nn focalize	Analyzes and plots a axial focus measurement of scan_number.nn.
scan_number.nn sptip	Analyzes and plots a sky tip measurement.
Commands Specific to *line*	
fbdata	Tells *line* that you wish to analyze filter bank data.
hcdata	Tells *line* that you wish to analyze Millimeter Autocorrelator (MAC) data.
g#	Displays the most recent chopper wheel calibration array for filter bank number # (where # is either 1 or 2).
gget# scan_number	Gets and displays the calibration scan associated with filter bank # of scan_number (where # is either 1 or 2).
scan_number f	Gets and displays the first filter bank of scan_number.
scan_number s	Gets and displays the second filter bank of scan_number.
halves	Displays the average of two filter bank polarizations acquired in "parallel mode".
gcopy	Make a laser printer plot of the graphics screen.

Table 2.3: Analysis Procedures in *line*

Command	Function
badch	Starts interactive bad channel flagging procedure.
bset	Interactive procedure to set baseline fit parameters.
nfit = n	Sets the baseline order to n.
baseline xx	Fits, subtracts, and plots the resulting baseline.
gset	Interactive procedure to set gaussian fit parameters.
gauss	Fits gaussians.
gparts	Plots individual gaussian fits (for multiple gaussians) and lists height, FWHP width, and position for each gaussian.
gdisplay	Plots sum of gaussian fits and lists characteristics.
center_scan_number fivel#	Processes the spectra for a total power spectral line five-point measurement from filter bank #, where # is either 1 or 2.

- *CLASS* and *uni2class* can access the data file at the same time. This means that you can read the *CLASS* file at the same time as you are writing to it.
- *uni2class* will overwrite existing output files without warning. Be careful!
- Only LSR and heliocentric velocities, equatorial coordinates, and the standard small-field projection are handled correctly.
- No distinction is made between radio and optical velocity definitions.
- Continuum data are not handled.
- The sdd and *CLASS* headers do not map onto each other exactly, but nearly all of the important parameters are mapped.

2.4.2 Drawspec

Drawspec is a PC-based analysis program written by Harvey Liszt. The public PC in the control room at the 12m has a current copy of *Drawspec* for observer use. To port your data to *Drawspec*, you must write a single-dish FITS file of your data. The program *uni2fits* will do this for you. Just issue the command

```
% uni2fits
```

at the unix prompt on any of the workstations at the 12m to start the program. You will be asked a series of questions by *uni2fits* which should be self-explanatory. Once you have a single-dish FITS file, you can start the *Drawspec* program and use the "scanmstr" utility in *Drawspec* to import the single-dish FITS file. See Harvey Liszt's home page at

Table 2.4: Correspondence Between Subscan Codes and CLASS Telescope Identifiers

Subscan	CLASS Telescope Identifier
Filter Bank Data	
01	12M-FB11
02	12M-FB12
03	12M-FB21
04	12M-FB22
Millimeter Autocorrelator (MAC) Data	
2 IF Mode	
11	12M-MAC11
12	12M-MAC12
4 IF Mode	
11	12M-MAC11
12	12M-MAC21
13	12M-MAC12
14	12M-MAC22
8 IF Mode	
11	12M-MAC11
12	12M-MAC12
13	12M-MAC13
14	12M-MAC14
15	12M-MAC15
16	12M-MAC16
17	12M-MAC17
18	12M-MAC18

http://www.cv.nrao.edu/~hliszt/programs.html for more information on *Drawspec* and its affiliated programs.

2.5 Data Archiving and Export

When you have finished your observations, an archive tape of the observers' files will be made and sent to the Tucson office. If you submit a Data Tape Request Form, the staff will create an export tape of your data and mail it to your home institution. We offer two types of export tapes: an ASCII tape following the FITS standard or a tar-format copy of your sdd files.

Chapter 3

Instrumentation

3.1 Telescope Site Layout

The 12m is located on the southwest ridge of Kitt Peak, about two miles below the top of the mountain. Other telescopes on the southwest ridge are the NRAO 25m VLBA antenna and the McGraw-Hill Observatory 1.2m and 2.4m optical telescopes. A drawing of the 12m site layout is given in the *Visitor's Guide to the NRAO 12m Telescope* and can be found on the NRAO Tucson Home Page (http://www.tuc.nrao.edu/Tucson.html).

Three rooms are available in the dome for observer use. During scheduled observing time, you will normally want to sit in the control room at the observer's console so that you can communicate with the operator. An adjacent "breezeway" room has an additional workstation and work area. A third room, called the "observer lounge", is available for work, data reduction, and private phone calls. This room has a couch that can be used for naps. If two observing teams are sharing time on the telescope, the data reduction station in the observer lounge is reserved for the team not currently observing. The team not currently observing should stay out of the control room if at all possible. If more than two observing teams are sharing time at the telescope, they should negotiate the use of the observer lounge.

3.2 Telescope Optics

The 12m employs "bent Cassegrain" optics for all of the receivers used by visiting observers. A few test and special purpose receivers including the holography receiver are mounted at the prime focus. A diagram of the optics is given in Figure 3.1. The primary mirror is a 12.0 meter paraboloid of 72 aluminum panels. The position of each panel can be adjusted by stand-off bolts. The subreflector (secondary mirror) is mounted at the prime focus and is supported by a quadrapod feed leg structure. The subreflector mounting box contains the nutation (beam switching) electronics and the solenoid drivers for the switching. The box also contains a gas discharge noise source and associated electronics. The feed horn of the noise source protrudes from a hole in the center of the machined-aluminum hyperboloid subreflector. Under normal operation, the noise tube is covered with a cone reflector (called the "Cone of Silence") to minimize standing waves in the IF passband. **If you would like**

to use the noise tube for calibration, you must let the operator know so that he can remove the cone reflector.

The subreflector box is located in a focus-translation mount with three degrees of freedom of movement. The subreflector can be moved in and out along the radio axis to adjust for axial focus changes, it can be moved in an “up-down” (or “north-south”) direction to compensate for north-south focus changes, or east-west to adjust for optimum azimuth position.

The tertiary or central mirror is a rectangular flat mirror with azimuth and elevation position adjustments. The elevation position of the mirror is periodically measured and then clamped down. The azimuth position can be rotated to direct the radio beam to any of the four receiver bays, located behind the main reflector. The central mirror positioning is motorized and under servo control from the control room, making it possible to use more than one receiver during a single observing run, though not simultaneously.

The central mirror directs the beam to one of the four quaternary mirrors over each receiver box. The quaternary mirrors are oval flats and have one degree of freedom for position adjustment. The optics following the quaternary mirrors are contained within the receiver boxes and are usually different for each receiver.

The alignment of the mirrors is done optically. Small optical mirrors are fixed to the tertiary and quaternary mirrors. A laser is mounted in the subreflector position and the mirrors are adjusted so that the laser beam spot is centered on the receiver lens. The beam also may be autocollimated at the subreflector to achieve the most precise alignment.

3.3 Receivers

All of the receivers in use at the 12m employ heterodyne mixers (sometimes called “coherent detectors”) which use superconducting-insulating-superconducting (SIS) junctions. The SIS junctions are housed in a dewar which is part of a closed-cycle cryostat with temperature stages at 20 K and 4 K. The 20 K stage is cooled by a conventional compressed helium refrigerator system; the 4 K stage is cooled by a separate Joule-Thomson unit. The two receivers are mounted in upright structures, variously known as “rockets” or “inserts”. The inserts are wholly self-contained receiver units, and may be removed independently, albeit by warming the mother dewar. A local oscillator (LO) signal, provided by a Gunn oscillator, is injected into the mixer or diplexed with the incoming radio frequency (RF) signal. The output of the mixer is an intermediate frequency that is the difference between the LO and RF signal frequencies. The SIS junctions in the 3 and 2mm receivers have tunable backshorts, which can be adjusted to resonantly cancel the unwanted sideband, and are essentially single sideband (SSB) mixers. A harmonic generator is switched into the optical path of the receiver to allow precise measurement of the sideband rejection in the 2 and 3mm receivers. The image sideband of the 1mm receiver is rejected by inserting a Martin-Pupplet filter into the LO path. At most frequencies the image sideband can be rejected to $\geq$20 dB.

Table 3.1 lists the current tuning ranges and typical system temperatures for all of the facility 12m receivers, while Table 3.2 lists representive telescope efficiencies.

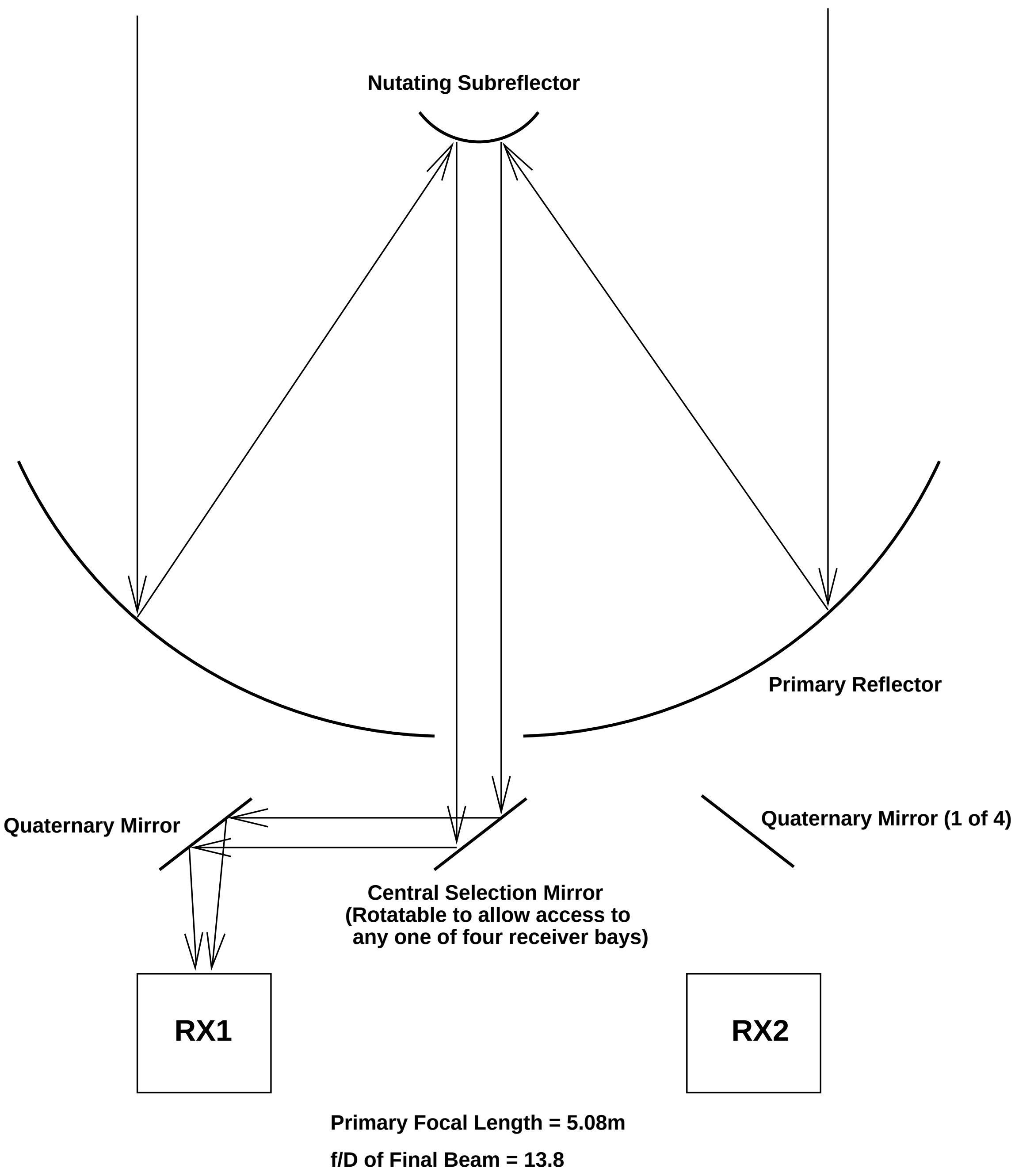

Figure 3.1: 12m Telescope Optics

Table 3.1: 12m Receiver Characteristics

Receiver	Tuning Range (GHz)	Approximate T_{sys}(SSB) (K)
3mmlo	68–90	170–225
3mmhi	90–116	160–350
2mm	130–170	180–400
1mmlo	200–265	400–900
1mmhi	260–300	800–1200
1mm8ch	215–245	700

Table 3.2: 12m Telescope Efficiencies

Frequency (GHz)	Beamwidth (arcsec)	$\eta_A{}^a$	$\eta_l{}^b$	$\eta_{fss}{}^c$	$\eta_m^*{}^d$
70	90	0.52	0.94	0.68	0.98
90	70	0.51	0.94	0.68	0.95
115	55	0.48	0.94	0.68	0.85
145	43	0.45	0.94	0.68	0.80
230	27	0.32	0.94	0.68	0.50
300	21	0.22	0.94	0.68	0.30

[a]η_A = aperture efficiency
[b]η_l = rear spillover and scattering, blockage, and ohmic loss efficiency
[c]η_{fss} = forward scattering and spillover efficiency
[d]η_m^* = corrected main beam efficiency (percent of power in the main diffraction beam relative to the outlying error beam)

3.3.1 1mm Array Receiver

The 1mm Array receiver is designed for rapid mapping of spectral lines in the 215 – 240 GHz range (notably J = 2 → 1 CO and its isotopomers). The receiver places 8 independent beams on the sky in a 2 × 4 array; each beam is separated from its nearest neighbor by 87″ (see Figure 3.2). The FWHM of each beam at 230 GHz is ∼30″, hence the telescope must be stepped in position to fill in the beams if Nyquist sampling is desired.

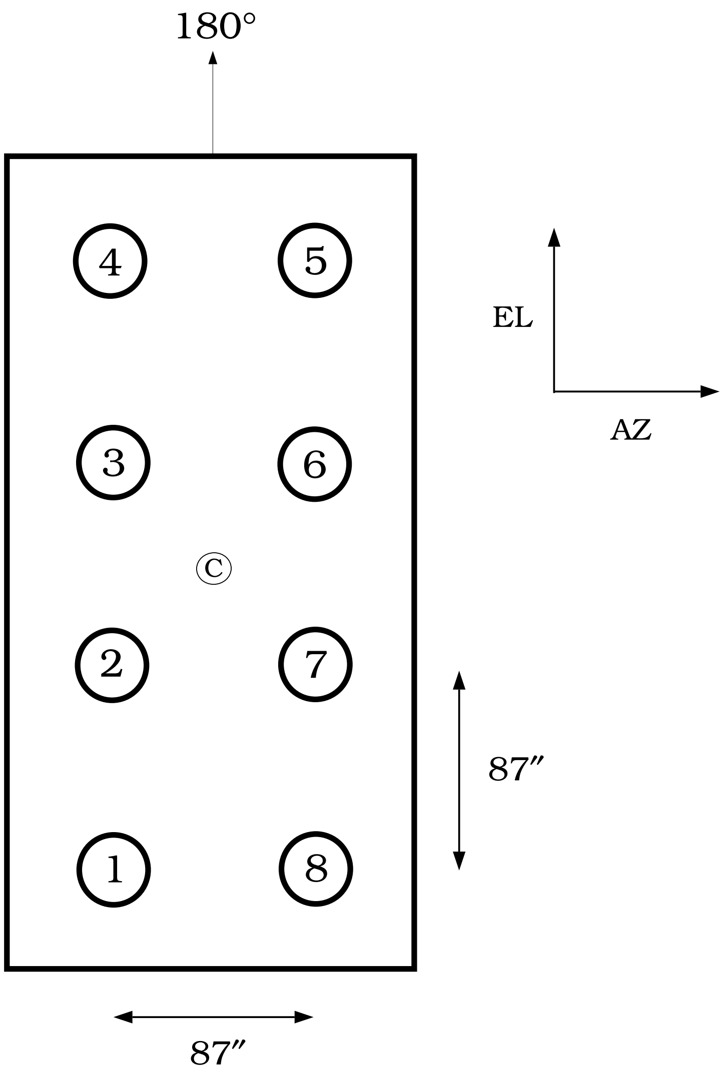

Figure 3.2: 1mm Array receiver layout

The 1mm Array receiver is intended for use with the Millimeter Autocorrelator (MAC) and eight channel IF processor. The Millimeter Autocorrelator (MAC) and IF processor can accept 8 IF channels of 600 MHz or narrower bandwidth, or 4 IF channels of 600 MHz bandwidth. A complete description on how to observe with the 1mm Array receiver is given in the companion document *Observing with the NRAO 1mm Array Receiver*.

3.3.1.1 1mm Array Rotator and Positioning Conventions

The entire 1mm Array receiver cryostat and optics assembly is housed in a precision rotation mechanism which can rotate the orientation of the array of beams to an arbitrary angle on the sky. Thus, the array may be positioned to take advantage of a particular source geometry. Furthermore, the 1mm Array rotator can then track parallactic angle so that as the source moves across the sky in hour angle, the orientation of the array is the same in the RA-DEC frame (because the 12m is an AZ-EL telescope, parallactic angle rotation must be taken into account). The rotation center of the array is defined to be its geometric center, *i.e.*, the center of the box defined by beams 2, 3, 6, and 7 (see Figure 3.2).

Three different angles come into play in describing the positioning and movement of the rotator:

Source Parallactic Angle: The parallactic angle is defined as the angle between lines of constant azimuth and hour angle. Thus, it is a function of the azimuth, elevation, hour angle, and declination of the source. The convention employed at the 12m is as follows:

When a source is on the Prime Meridian (0 Hour Angle) in the south, parallactic angle is defined to be 0°. While the source is above the horizon in the south, parallactic angle always increases with time. When the source is on the Prime Meridian (upper culmination) in the north, parallactic angle is defined to be 180°. In the north, parallactic angle decreases with time.

Rotator Control Angle: The angle describing the rotation of the 1mm Array rotator relative to its position encoders. This angle is displayed on the Status monitor. The convention is stated as follows:

When the telescope is pointing due south (180° azimuth) and the long dimension of the array is aligned along the Prime Meridian (up and down in the elevation direction), with beams 4 and 5 at high elevation (and high declination), the array has a rotator control angle of 0°. If the rotator is turned so that beams 4 and 5 move toward larger azimuth, the rotator control angle increases.

User Position Angle: The user-defined position angle is available to allow the user to position the rectangular array of beams in the RA/DEC frame to achieve optimal mapping efficiency according to the geometry of the source. The most common example of this would be to position the long dimension of the array of beams along the major axis of a galaxy. The convention for defining User Position Angle is as follows:

The user-defined position angle follows the usual astronomical position angle convention. Position angle increases toward the east (increasing Right Ascension). Note that this convention is independent of whether the source is north or south of the zenith.

Table 3.3: 1mm Array Azimuth and Elevation Offsets Relative to Array Center

Beam Number	Azimuth Offset ($''$)	Elevation Offset ($''$)
1	-43.5	-130.5
2	-43.5	-43.5
3	-43.5	43.5
4	-43.5	130.5
5	43.5	130.5
6	43.5	43.5
7	43.5	-43.5
8	43.5	-130.5

3.3.1.2 Pointing and Mapping Offsets with the 1mm Array Rotator

The rotation and tracking center of the array is at its geometric center, where no beam exists. We take account of this fact in pointing and focus measurements by allowing the user to specify a beam to point or focus on and then calculating the pointing center of the array based on this measurement.

When the array is rotated from its "null" control angle of 0°, the position of the beams are given by the equations for a Cartesian coordinate system rotation. In the (AZ,EL) frame the position of an individual beam is given by

$$\begin{aligned} \Delta A_i &= A_0 - [A_i \cos(\theta - \theta_0) + E_i \sin(\theta - \theta_0)] \\ \Delta E_i &= E_0 - [E_i \cos(\theta - \theta_0) - A_i \sin(\theta - \theta_0)] \end{aligned} \tag{3.1}$$

where A_0 and E_0 are the azimuth and elevation pointing correction for the center of the array, θ_0 is the hardware control angle of the array in its null position (0°), θ is the rotator control angle, and A_i and E_i are the azimuth and elevation offsets of the individual beams relative to the geometric center, and are given by Table 3.3

If you are not tracking parallactic angle (*e.g.* for a pointing check), then you will be observing in an (AZ,EL) frame and all positioning offsets should be in AZ and EL. If you are tracking parallactic angle, you will be observing in an (RA,DEC) or (lII,bII) frame and mapping and beam offsets should be given in RA and DEC.

Relations similar to Equations 3.1 exist for (RA,DEC) (or (lII,bII)) offsets when the array is rotated by a user position angle. The equations describing these offsets are

$$\Delta RA_i = -RA_i \cos(\theta) + DEC_i \sin(\theta) \tag{3.2}$$

$$\Delta DEC_i = DEC_i \cos(\theta) + RA_i \sin(\theta) \tag{3.3}$$

where θ is the position angle and RA_i and DEC_i are the RA and DEC offsets of each beam relative to the rotation center, when the array is at 0° position angle. These offsets are the same as in Table 3.3, with RA corresponding to the Azimuth column and DEC to the Elevation column. If you wish to convert arc seconds on the sky to seconds of time in RA, remember to divide by 15 cos(DEC).

3.4 The Local Oscillator System

Mixer receivers require a local oscillator signal. For spectral line work, the LO signal must be phase and frequency stable to an accuracy of at least 1 part in 10^5. The purpose of the LO system is to phase lock the LO source, which is otherwise a free-running oscillator. LO sources used at the 12m are solid state Gunn oscillators. The power required of the LO source by present generation millimeter-wave mixers precludes the direct use of a harmonic of a low frequency synthesizer. At the 12m, a precise synthesizer harmonic is used as a comparison frequency for the phase lock loop.

A 5 MHz rubidium oscillator is multiplied by 20 to give a frequency of 100 MHz. This 100 MHz drives a comb generator, thus enabling any multiple of the 100 MHz in the range 1-2 GHz to be selected by a filter. Either the 18th or the 19th (1.8 or 1.9 GHz) is usually selected; a frequency between 50 and 150 MHz is then added and an oscillator is phase locked to the result. In this way a spectrally pure signal in the range 1.85 to 2.05 GHz is generated.

This nominal 2 GHz signal is then fed up to the receiver and used to drive a harmonic mixer. The nth harmonic of the 2 GHz signal (n may be any integer from ten to seventy, or higher) then mixes with a portion of the receiver LO frequency to produce the lock IF frequency. For the Gunn oscillator systems, F2 = 100 MHz. The phase lock of the Gunn is completed by phase detecting this beat frequency with a synthesized loop offset frequency as a reference. The loop offset frequency is generated by a tunable Fluke synthesizer.

The phase loop will lock when the LO frequency differs from the nth harmonic of the 2 GHz source by the loop offset frequency. This means, of course, two lock points, one with the LO above the nth harmonic and the other with the LO below. These two points will be separated by twice the loop offset frequency (200 MHz). The computer tests the loop for lock while taking data and stops taking data if the loop is found to be unlocked.

The synthesizer frequency is computed from the following equation:

$$f_{syn} = \frac{\frac{(f_{sky}+jf_{IF})}{m} + kf_{lock}}{N} \tag{3.4}$$

where f_{syn} is the synthesizer frequency, f_{sky} is the sky frequency of the emission (the rest frequency with Doppler corrections), j = +1 for lower sideband and −1 for upper sideband, f_{IF} is the IF frequency/indexfrequency!IF, m is the factor by which the LO frequency is multiplied before injection into the mixer, k = −1 for the lower lock sideband and +1 for the upper lock sideband, f_{lock} is the the phase lock loop offset frequency, and N is the synthesizer harmonic. The four permutations of j and k are given by a parameter "SB" (for "sideband") that is entered into the control computer.

The control computer calculates two synthesizer settings (corresponding to different harmonic numbers N) for a given rest frequency, source Doppler velocity, and SB value. The operator can switch between these two settings by turning a knob on the synthesizer control chassis. The computer chooses the synthesizer setting so that one is usually slightly above 1.9 GHz and the other slightly below. Both of these synthesizer settings are updated by the computer to reflect changing Doppler velocity as a result of the LSR reference frame or diurnal variations. A manual synthesizer setting can be entered from this chassis so that the receiver can be tuned without the aid of the computer if that is desired.

When tuning the receiver, the operator and observer must take care that the LO is locked to the correct harmonic and loop sideband. Two tests can be performed to assure that these conditions are met. First, if you try to lock to the wrong lock sideband, a "comb" of frequency spikes will appear on the spectrum analyzer. If this happens, turn the tune dial until the main spike moves off the edge of the screen and then returns. You must then perform a harmonic check. This is done by opening the phase lock loop (*i.e.* turning the phase lock circuitry off) and switching to the other synthesizer harmonic on the synthesizer control chassis. If the tuning is correct, the beat signal on the loop spectrum analyzer will appear at the same frequency for either harmonic. If these two tests are passed, the observer can be confident that he is locked to the correct frequency. A final, and conclusive, method of checking LO tuning is to look for a strong astronomical spectral line in the band, if one exists. For continuum observations, the precise frequency of phase lock is usually of little importance; observers sometimes choose to run "open loop" for simplicity of operation. Many of the receivers are more stable when phase locked, however.

3.5 The IF Section

All mixer receivers at the 12m produce an intermediate frequency of 1.5 GHz. The IF signal emerging from the receiver dewar must be further amplified and processed before detection by the spectral line and continuum backend devices. A two-channel IF system situated on the telescope performs this function. All the mixer receivers, except the 1mm Array system, use this same processor; the switch from one receiver to another is done remotely from the control room (see §3.4).

The incoming signal first passes into an automatic leveling module. This device is used in spectral line observations to keep the input signal to the filter banks at a constant level, thus improving the performance of the filter banks. As this device will level out all continuum signals, it is turned off by computer command when continuum observations are underway. A manual switch in the control room can also turn off the device. After leaving the Leveler Module, the signal is further amplified and filtered. It is then split into two paths, one for spectral line signals and one for continuum. For continuum applications, the 1.5 GHz signal is detected and passed directly to the backend continuum signal processors.

The spectral line signal must be mixed down to the baseband frequencies at which the filter banks operate. The IF Processor Module performs this function. The incoming 1500 MHz signal is first upconverted to 2442 MHz. The mixer signal for this upconversion originates with a tunable Fluke synthesizer in the control room. The frequency of the mixing can be changed by small amounts and the two IF channels can be controlled by separate Fluke synthesizers, if desired. This affords the observer some flexibility in setting up his observations. For example, the IF might be changed to get spectral lines in opposite

Table 3.4: 12m Filter Spectrometer Characteristics

Filter Bandwidth[a]	Channels (Filters) per Bank	Filter Banks Available
2 MHz	256	2
1 MHz	256	2
500 kHz	256	1
250 kHz	256	1
100 kHz	256	1
30 kHz[b]	128	1

[a]**NOTE:** This is the FWHM channel width. See Appendix D for further details.
[b]Series option only.

sidebands to fall within the bandpass. One of the channels could also be offset in frequency relative to the other. The primary restriction to these changes is that the spectral line emission must fall within the 600 MHz bandpass of the first IF amplifier. Chapter 5, Spectral Line Observing, provides a more detailed description of these options.

3.6 Spectrometers

3.6.1 Filter Banks

The 12m has eight filter spectrometers available for spectral line work. The multiplexer will provide two spectra with a total number of spectral channels not in excess of 512. Thus, it is always possible to record simultaneously the output of two filter banks. Except for the 30 kHz bank, all of the filter banks have two independent 128 channel sections. You can configure these banks in one of two ways. In the "series" option, the two sections are placed end to end in frequency space, *i.e.*, the 256 channels are sequential in frequency. In the "parallel" mode, the two sections are used independently to accept different receiver (polarization) channels. The series mode is appropriate for observations requiring a large bandwidth. The parallel mode is useful for narrow band observations in which two different spectral resolutions are needed. Additional discussion on the use of the filter banks is given in Chapter 5.

Table 3.4 provides a list of the spectrometers. The resolutions listed are the filter half power widths and their separations. The 2 MHz filter banks work at a center frequency of 342 MHz and thus directly accept the output of the IF processor discussed above. The other filter banks work at a center frequency of 150 MHz and require that the 342 MHz input signal be further down-converted.

3.6.2 Millimeter Autocorrelator (MAC)

The Millimeter Autocorrelator (MAC) (MAC) is a correlation spectrometer with a digital section similar in design to that used at the Green Bank Telescope (GBT). The full bandwidth for any given observation is pre-filtered through a set of anti-aliasing filters, and then each IF is sampled in three levels and autocorrelated.

The 65536 spectral channels of the spectrometer can be divided among up to 8 independent IF channels. As such, it matches well with the 1mm Array receiver, as well as with the dual-polarization channel, single beam receivers. The maximum useable bandwidth of the instrument is 1200 MHz. Table 3.5 summarizes the currently available Millimeter Autocorrelator (MAC) observing modes.

3.6.3 Continuum Backend

Continuum data at the 12m is acquired by a two channel, four phase digital backend (DBE). The DBE can record two switch phases and two calibration phases. The calibration phases can be generated by the synchronous emission of a noise diode, which is available at 3 mm wavelengths only. The DBE also generates a signal/reference pulse to move the subreflector at a default switching rate of 1.25 Hz, so that each phase of a four phase switching cycle lasts 125 ms. The DBE blanks the input signal (*i.e.* stops taking data) while the subreflector is in transition from one position to another. The blanking properties are regularly adjusted by the 12m staff.

3.7 Computer Equipment

The 12 Meter Telescope computer system is composed of a network of Sun workstations. The telescope control and primary data analysis functions are controlled by a dual-processor Sparcstation Ultra II. The control program is a C-language-based interface package called RAMBO. The RAMBO interface handles all of the functions of data acquisition, including communication with the VxWorks device drivers which run the spectrometers, receivers, and other devices associated with a particular measurement. Most major analysis packages are available on any of the telescope workstations.

Table 3.5: Millimeter Autocorrelator (MAC) Configurations

Bandwidth and Channels		Useable Bandwidth and Channels[1]		$\Delta\nu^2$	Resolution
(MHz)	Channels	(MHz)	Channels	(kHz)	(kHz)
2 IF Modes					
800	2048	600*	1536	390.6	781.2
800	4096	600	3072	195.3	390.6
400	4096	300*	3072	97.6	195.3
400	8192	300	6144	48.8	97.6
200	8192	150*	6144	24.4	48.8
200	16384	150	12288	12.2	24.4
100	16384	75*	12288	6.1	12.2
100	32768	75	24576	3.0	6.1
4 IF Modes					
800	1024	600*	768	781.2	1562.0
800	2048	600	1536	390.6	781.2
400	2048	300*	1536	195.3	390.6
400	4096	300	3072	97.6	195.3
200	4096	150*	3072	48.8	97.6
200	8192	150	6144	24.4	48.8
100	8192	75*	6144	12.2	24.4
100	16384	75	12288	6.1	12.2
8 IF Modes					
800	512	600*	384	1562.5	3125.0
800	1024	600	768	781.2	1562.0
400	1024	300*	768	390.6	781.2
400	2048	300	1536	195.3	390.6
200	2048	150*	1536	97.6	195.3
200	4096	150	3072	48.8	97.6
100	4096	75*	3072	24.4	48.8
100	8192	75	6144	12.2	24.4

[1] The useable bandwidth takes account of the 75% efficiency of the analog filters.

[2] **NOTE:** This is the frequency sampling interval, not the FWHM channel width, for a given channel. The FWHM channel width is 2.0 times this value. See Appendix D for details.

All values in this table refer to each IF.

Modes tagged with a $*$ are produced by dropping the last half of the lags.

Chapter 4

Tracking, Pointing, and Focus

4.1 Tracking Capabilities

The 12 Meter Telescope can track both stationary (sidereal) sources or fast moving sources such as the Sun, Moon, planets, comets, or satellites (called "ephemeris objects"). The positions of stationary sources may be entered into source catalogs by the observer or directly into the on-line system by the operator. Stationary source positions may be given as

- Apparent equatorial positions (already precessed),
- Equinox B1950 or J2000 equatorial positions, or
- Galactic coordinate positions (lII, bII).

An example of the 12m catalog format is the following:

```
18:27:17.3  01:13:23.0  B1950  SERMM1     8.0 LSR RAD
18:27:28.0  01:10:45.0  B1950  SERMM2     8.0 LSR RAD
18:27:27.3  01:11:55.0  B1950  SERMM3     8.0 LSR RAD
18:27:24.7  01:11:10.0  B1950  SERMM4     8.0 LSR RAD
18:27:18.9  01:12:02.0  B1950  SERMM5     8.0 LSR RAD
18:27:25.4  01:12:02.0  B1950  SERMM6     8.0 LSR RAD
18:27:22.0  01:12:30.0  B1950  SERCTR     8.0 LSR RAD
```

where

column 1 = right ascension (HH:MM:SS.S) or galactic longitude (DDD.DDDDD),

column 2 = declination (DD:MM:SS.S) or galactic latitude (DD.DDDDD),

column 3 = coordinate epoch (B1950, J2000, APPARENT, or GALACTIC),

column 4 = source name,

column 5 = source velocity,

column 6 = source velocity reference frame (LSR, HEL, GEO, or TOP), where

LSR = local standard of rest velocity reference frame,

HEL = heliocentric velocity reference frame,

GEO = geocentric velocity reference frame, and

TOP = topocentric velocity reference frame,

column 7 = source velocity type (RAD, OPT, or REL), where

RAD = radial velocity type,

OPT = optical velocity type, and

REL = relativistic velocity type,

The sky frequency equations corresponding to the above velocity types are given in Equations 5.4.

4.1.1 Ephemeris Objects

To track ephemeris objects (comets, asteroids, *etc.*), the control system requires three positions, centered upon the present time. The tracking algorithm then makes a cubic spline interpolation to determine the source position at the specific time of observation. The observer must prepare a catalog in the correct format in order to observe ephemeris objects other than the planets and the Moon. The basic format needed by the control system is show below.

```
OBJ Hyakutake
VELFRAME LSR
VELTYPE RAD
#
# Ephemeris for Hyakutake,  0.000 H  9 APR 1996 to 23.700 10 APR 1996
#
D 45.7745 D 41.3975 J  50182.000720 0.00 55.84
D 45.7705 D 41.3822 J  50182.017387 0.00 55.86
D 45.7662 D 41.3670 J  50182.034053 0.00 55.89
D 45.7620 D 41.3517 J  50182.050720 0.00 55.91
D 45.7580 D 41.3363 J  50182.067387 0.00 55.93
D 45.7540 D 41.3212 J  50182.084053 0.00 55.94
D 45.7500 D 41.3058 J  50182.100720 0.00 55.95
D 45.7463 D 41.2907 J  50182.117387 0.00 55.96
D 45.7422 D 41.2755 J  50182.134053 0.00 55.97
D 45.7385 D 41.2603 J  50182.150720 0.00 55.97
D 45.7347 D 41.2452 J  50182.167387 0.00 55.97
D 45.7313 D 41.2300 J  50182.184053 0.00 55.97
```

where the first three lines are descriptors for the object name, velocity frame, and velocity type. The next three lines are comments. Each column thereafter is defined as follows:

D 45.7745 = the topocentric right ascension in degrees.

D 41.3975 = the topocentric declination in degrees.

NOTE: You can also use a geocentric right ascension and declination in the last two locations, but if you do you must enter the correct horizontal parallax (see below).

J 50182.000720 = the Modified Julian Date (mjd) of this record in the TT (Terrestrial Time, which used to be called Terrestrial Dynamical Time, or TDT) system. Note that TT = UTC + 63.184 sec after June 30, 1997.

0.00 = the horizontal parallax (the angle from you to the object to the center of the earth in arcseconds). The horizontal parallax is zero in this case since we are using topocentric coordinates. If one uses geocentric coordinates, the horizontal parallax must be non-zero and is given by:

$$\begin{aligned} HP &= \arcsin\left(\frac{6378.137}{\rho}\right) \\ \rho &\equiv \text{geocentric distance of object} \end{aligned}$$

55.84 = the topocentric velocity. Non-planets default to topocentric velocities. Planets default to geocentric positions and velocities.

After you create the ephemeris put it in a file with the extension `eph` in the observers home directory – `/home/obs/ini/comet.eph` for example.

If you do not have an ephemeris generation program, we have a copy of the "TBEG4" two body ephemeris generator program written by Don Yeomans which you can use. This program will produce a 12m-format ephemeris file given a set of orbital elements. Contact Jeff Mangum if you would like to use this program.

4.2 Tracking Limits

4.2.1 Elevation Limits

Mechanical limits constrain the movement of the telescope on both the azimuth and elevation axes. Under normal source-tracking operation, the control system software prevents the telescope from moving into these limits. The telescope is also equipped with fail-safe hardware limit switches that will turn the drive motors off and apply the brakes before the telescope can be damaged. When the telescope reaches a lower elevation of 15.0°, it begins to depress a safety spring on the elevation stop. Tracking can continue until the elevation drive motor begins drawing excessive current; this usually occurs at an elevation near 14.5°. A final limit switch is tripped at 13.8° elevation.

The control computer will allow a source to be tracked up to an elevation of 90°. The pointing equations diverge at the zenith, however, and elevations greater than 88° should be strictly avoided during observations. For routine observations, we recommend that you avoid elevations >80° if possible, since both tracking and pointing degrade in that range. For maintenance purposes only, the telescope can be driven to an elevation of 92° before tripping a final limit switch.

4.2.2 Azimuth Limits

To prevent the over-wrapping of cables, the telescope has hardware and software azimuth limits. The control system will not allow the telescope to rotate through 66.8° azimuth to acquire or track a source. As they rise, sources with declinations between 27° and 38.75° will pass through 66.8° azimuth above 15° elevation. When a rising source reaches an azimuth of 66.8°, the telescope will rotate 360° to re-acquire the source. The region of the sky where azimuth transitions occur is displayed in Figure 4.1. If an integration is in progress when the transition azimuth is reached, the integration is halted while the telescope rotates around to re-acquire the source. The integration is resumed when the source is reached again. If it is undesirable for this to happen, you should cease the integration before reaching the transition azimuth.

4.3 Tracking Error Tolerance

The 12 Meter Telescope is vulnerable to tracking errors produced by wind gusts. The tracking software has a provision for rejecting from the integration any data sample that was taken with the telescope off source. The basic timing cycle of the 12m control system is 100 milliseconds (0.1 sec). After each 100 ms interval, the system checks for error conditions such as tracking errors or a loss of frequency phase lock. If an error condition is detected, the data sample collected during the last 100 ms interval is not averaged with the rest of the data.

You can choose how much tracking error you are willing to accept. This number is called the "tracking tolerance" and is displayed on the on-line status monitor in the lower left-hand corner under the heading "TOL". The 12m typically experiences 3–4″ tracking errors under calm conditions. The tolerance is usually not set to less than 5″ for this reason. Typical choices for the tolerance are 5″ for 1.3 mm and shorter wavelength observations, and 10″ for 2 and 3 mm observations. Figure 4.2 shows the amount of signal that is lost by a given pointing error, expressed as fractions of a FWHP beamwidth.

4.4 Sequence of Position Computation Operations

The sequence of computer operations that is executed when seeking and then tracking a source is as follows:

1. Input RA-DEC (B1950, J2000, or current epoch) or galactic (lII,bII).
2. If B1950 position, precess to current date. If galactic coordinates, first precess to epoch B1950 The precessed position of a source is computed only when the source is first accessed.

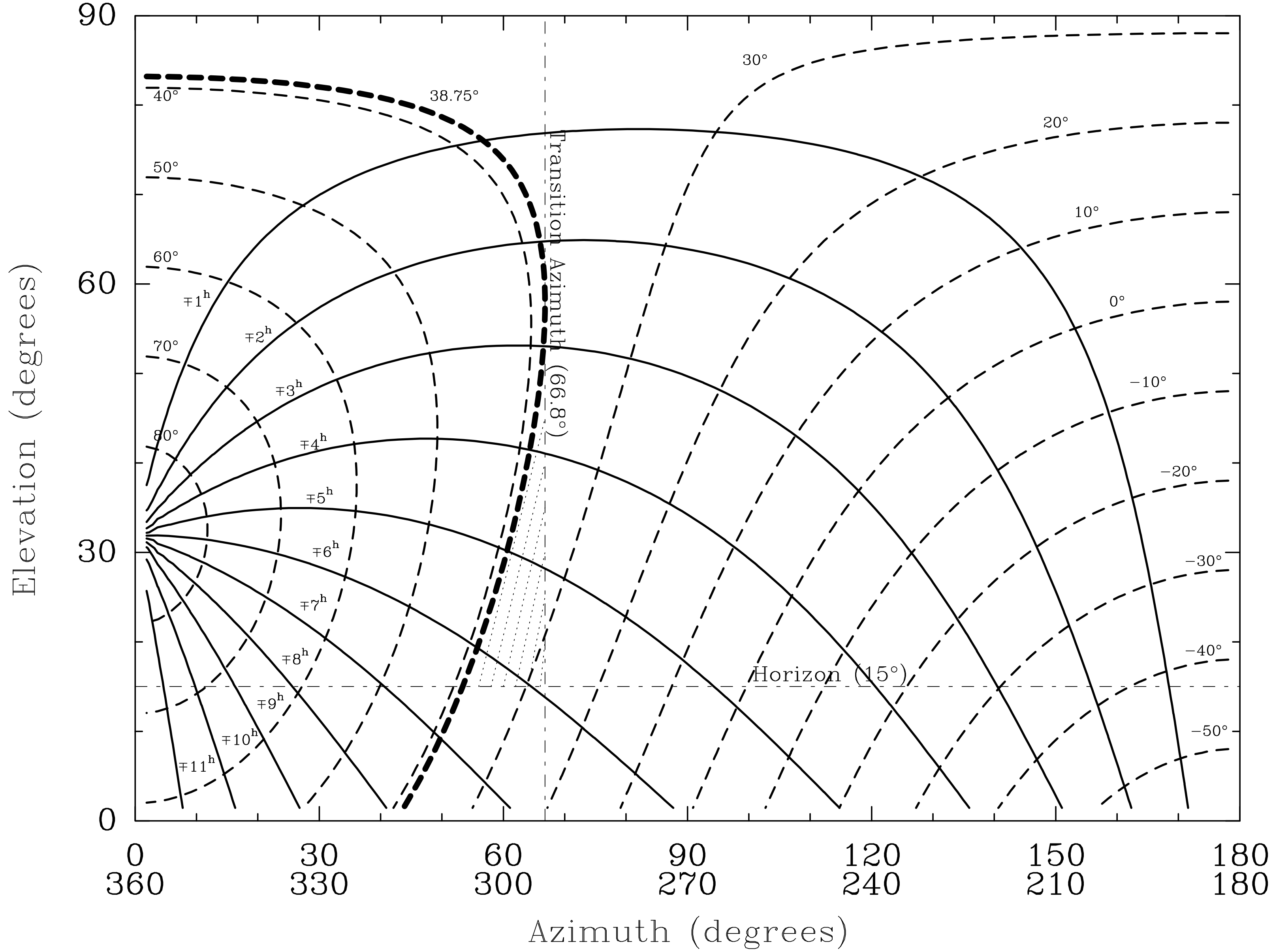

Figure 4.1: Local hour angle and declination versus azimuth and elevation for the 12m. The hatched region indicates the range of source declination where the telescope will undergo a 360° azimuth transition while tracking a rising source.

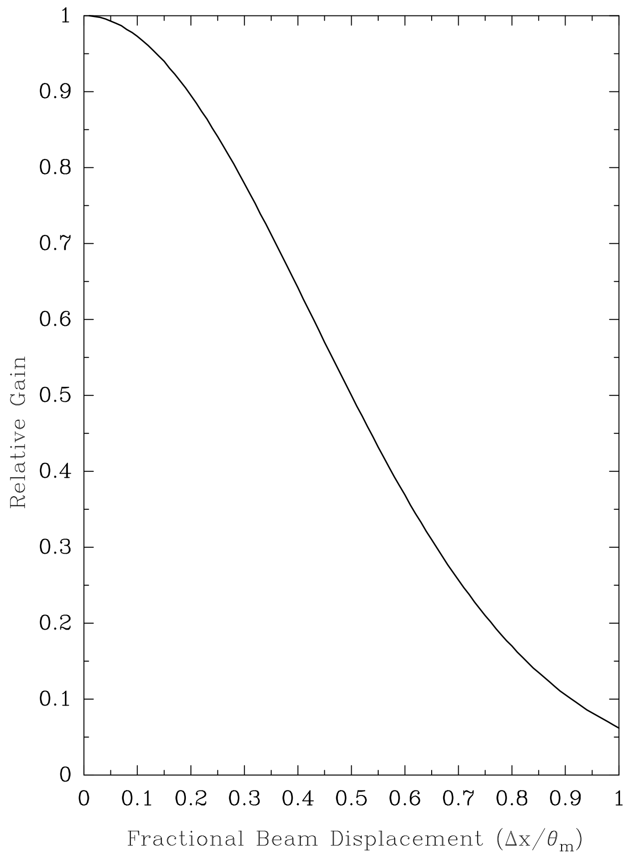

Figure 4.2: Loss of signal due to pointing error.

3. If source is an ephemeris object, interpolate to current UT.
4. Do spherical coordinate conversion from RA-DEC to AZ-EL.
5. Add azimuth and elevation encoder corrections as computed from Equations A.1, A.2, A.9, and A.10 (Appendix A).
6. Add azimuth and elevation pointing corrections.
7. Command telescope to the correct AZ-EL position.
8. Once every 10 seconds, go back to spherical coordinate conversion. Between loops, extrapolate AZ and EL drive rates every 100 ms to compute positions.

4.5 Subreflector Beam Throw

The 12 Meter Telescope is equipped with a nutating (chopping) subreflector that is used for beam-switched observations in both the spectral line and continuum modes. Other observing modes, such as position switching, are made with the subreflector locked in place. Obviously, the throw position of the subreflector, whether it is chopping or locked in place, affects the pointing of the telescope. The current 12m subreflector switches only in azimuth, although mount misalignments may produce a small component in the elevation direction (usually these are less than 1-2$''$). The pointing equations for the 12m are set up for 0 offset in subreflector position, *i.e.* with the subreflector axis aligned with the electrical axis of the primary reflector. When the subreflector is offset so that the telescope must be moved in the positive azimuth direction to bring the source into the beam, the subreflector is said to be in the "+BEAM". When the telescope must be moved in the negative azimuth direction to acquire the source, at least with respect to the +BEAM, the subreflector is in the "−BEAM". Figure 4.3 illustrates this convention. Both the spectral line and continuum backends are configured so that the +BEAM signal is positive and the −BEAM signal negative.

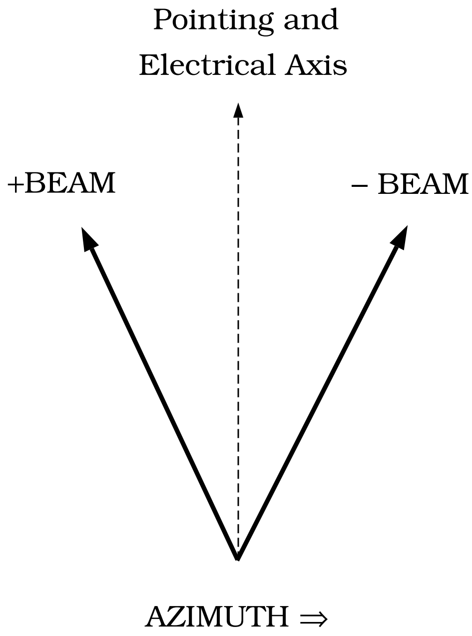

Figure 4.3: Subreflector +Beam/−Beam conventions.

The control system software takes account of the subreflector throw setting when positioning the telescope. The computer does not read the subreflector setting automatically, however; it depends upon the operator to manually set the throw value. The subreflector is physically set by turning two dials on the subreflector control chassis. Default values of subreflector throw are stored in the computer: for example, $\pm 2'$ for 3 mm and $\pm 1'$ for 1 mm. You can check the beam throw by making a continuum cross-scan on a strong source. Continuum mapping rows are explained in detail in Chapter 6.

4.6 Pointing

You are responsible for determining the residual azimuth and elevation pointing offsets, relative to the nominal telescope pointing. These offsets are usually of the order $10'' - 20''$ and often vary across the sky. In particular, the offsets often show an elevation dependence. The pointing of the 12m may drift over a period of several months by $10''$ or so, and you are cautioned not to assume that old pointing data are still valid. If a project requires accurate pointing, observers should budget 5 - 10% of their total observing time to pointing checks. High frequency projects, for which the FWHP of the main beam is $30''$ or less, obviously require more attention to the pointing.

You may perform pointing checks in either continuum or spectral line mode. Pointing sources must have an angular brightness distribution that is compact compared to the antenna beam. In addition, they must have well-determined positions and must be strong enough to point on in a reasonable amount of time, *e.g.* 10 minutes or less. The best pointing sources are the major planets Venus, Mars, Jupiter, Saturn, and Uranus, observed in continuum mode. These sources have strong flux densities throughout the millimeter band, although Uranus is faint at 3mm and longer wavelengths. To obtain complete sky coverage, particularly north of the zenith, the planets must be supplemented with other pointing sources. A tabulation of these sources and approximate flux densities at 3 and 1 mm is given in Table 4.1. This table includes the sources traditionally used at the 12m together with sources found useful at the IRAM 30m telescope. The sources with no listed flux density are on the order of 1 Jy in strength. It should be noted that the flux densities of many of the extragalactic sources in the table can be highly time-variable. For an up-to-date listing of measured 3mm fluxes, see http://dopey.haystack.edu/cmva/quasar.list.

The spectral line emission from a number of sources can be used for pointing purposes. Emission from rotational transitions of CO, HCN, and SiO are often strong enough and angularly compact enough to provide good pointing results. A list of spectral line pointing sources and their strong molecular emission lines are listed in Table 4.2.

4.6.1 Continuum and Spectral Line Five-Point Measurements

The five-point mapping option is the standard observing technique for determining the antenna pointing of the 12 Meter Telescope. Continuum five-point measurements can also be used to measure the flux density of a strong source with the highest precision, or the flux density of a source whose position is not exactly known. The five-point map consists of five successive ON/OFF **sequences** (for continuum and beam-switched spectral line measurements), or five successive ON and OFF measurements (for position-switched spectral line measurements), or five successive ON measurements with one associated OFF measurement (for total power spectral line measurements). The five **sequences** or ON measurements are positioned in azimuth and elevation relative to the nominal source position, as shown in Figure 4.4. The numbers identifying the positions give the time order in which the **sequences** are taken. The offset for each position ("HP" in Figure 4.4), is a selected offset (in arcsec) that is usually chosen to be close to half the HPBW of the telescope at the observing frequency. HP should be somewhat larger if the source is extended; for a planet that is resolved by the beam, chose HP to be approximately the semi-diameter

Table 4.1: Galactic and Extragalactic Continuum Pointing Sources

Source	α(B1950)	δ(B1950)	S_ν(3mm) (Jy)	S_ν(2mm)	S_ν(1mm) (Jy)
0003+380	00:03:22.3	+38:03:33	1.4		
0048−097	00:48:10.0	−09:45:24	1.8		
0106+013	01:06:04.5	+01:19:01	0.9		
0112−017	01:12:43.9	−01:42:55			
0119+041	01:19:21.4	+04:06:44	1.2		
0133+476	01:33:55.1	+47:36:13	2.8		
0135−247	01:35:17.1	−24:46:09	1.3		
0202+149	02:02:07.4	+14:59:51	3.7		
W3(OH)	02:23:16.5	+61:38:57	3.8		
0224+671	02:24:41.2	+67:07:40	0.8		
0235+164	02:35:52.6	+16:24:04	1.5		
0300+471	03:00:10.1	+47:04:34	1.5		
3C84	03:16:29.6	+41:19:52	4.4		
0336−019	03:36:59.0	−01:56:17	2.1		
NRAO150	03:55:45.3	+50:49:20	2.8		
0415+379	04:15:02.1	+37:54:29	5.7	4.8	
0420−014	04:20:43.5	−01:27:29	2.9		
0426−380	04:26:54.7	−38:02:52	2.9		
3C120	04:30:31.6	+05:15:00	1.5		
0439+360	04:39:33.8	+36:01:15	1.1		
0454−234	04:54:57.3	−23:29:29	2.1		
0458−020	04:58:41.3	−02:03:33	1.9		
0521−365	05:21:12.9	−36:30:17	4.6		
0528+134	05:28:06.8	+13:29:42	1.9	4.5	
TAUA	05:31:30.0	+21:59:00			
0552+398	05:52:01.3	+39:48:22	2.3		
0605−085	06:05:36.0	−08:34:20	1.7		
0607−157	06:07:26.0	−15:42:03	5.5		
0642+449	06:42:53.0	+44:54:31	1.4		
0716+714	07:16:13.0	+71:26:15	0.3		
0727−115	07:27:58.1	−11:34:53	1.2		

Table 4.1: Galactic and Extragalactic Continuum Pointing Sources (continued)

Source	α(B1950)	δ(B1950)	S_ν(3mm) (Jy)	S_ν(2mm)	S_ν(1mm) (Jy)
0735+178	07:35:14.1	+17:49:09	0.5		
0736+017	07:36:42.5	+01:44:00	3.2		
0805−078	08:05:49.6	−07:42:23	1.2		
0814+425	08:14:51.7	+42:32:08	1.3		
0820+560	08:20:53.2	+56:02:27	1.0		
OJ287	08:51:57.3	+20:17:58	1.8	1.1	
0923+392	09:23:55.3	+39:15:24	4.5	3.5	
1034−293	10:34:55.8	−29:18:27	0.6		
1039+811	10:39:27.8	+81:10:24	0.4		
1044+719	10:44:49.8	+71:59:27	1.5		
1055+018	10:55:55.3	+01:50:04	2.0		
1116+128	11:16:20.8	+12:51:07	0.3		
1156+295	11:56:57.8	+29:31:26	1.7		
3C273	12:26:33.2	+02:19:43	25.2	15.0	10
VIRA	12:28:17.6	+12:40:02	5.4		
1244−255	12:44:06.8	−25:31:28	1.8		
3C279	12:53:35.8	−05:31:08	14.9	12.9	
1308+326	13:08:07.6	+32:36:40	1.5		
1313−333	13:13:20.1	−33:23:10	1.4		
CENTA	13:22:31.7	−42:45:30	9.4		
1334−127	13:34:59.8	−12:42:10	6.5	4.9	
1354+195	13:54:42.1	+19:33:44	0.8		
1413+135	14:13:33.9	+13:34:17	1.3		
1418+546	14:18:06.2	+54:36:58	1.0		
1502+106	15:02:00.2	+10:41:18	0.8		
1504−167	15:04:16.4	−16:40:59	1.1		
1510−089	15:10:08.9	−08:54:48	1.2		
1514−241	15:14:45.3	−24:11:23	1.2		
1546+027	15:46:58.3	+02:46:06	2.0	2.7	
1548+056	15:48:06.9	+05:36:11	2.1	1.3	
1611+343	16:11:47.9	+34:20:20	2.1	1.1	

Table 4.1: Galactic and Extragalactic Continuum Pointing Sources (continued)

Source	α(B1950)	δ(B1950)	S_ν(3mm) (Jy)	S_ν(2mm)	S_ν(1mm) (Jy)
1622−253	16:22:44.1	−25:20:52	0.4	0.5	
1633+382	16:33:30.6	+38:14:10	1.6		
1637+574	16:37:17.4	+57:26:16	1.1		
1638+398	16:38:48.2	+39:52:30	1.0		
3C345	16:41:17.6	+39:54:11	4.8	1.5	
1655+077	16:55:44.0	+07:45:59	1.0		
1657−261	16:57:47.7	−26:06:29	1.8		
NRAO530	17:30:13.5	−13:02:46	5.8	8.4	
1732+389	17:32:40.5	+38:59:47	1.0		
1741−038	17:41:20.6	−03:48:49	2.2		
1749+096	17:49:10.4	+09:39:43	2.9	0.5	
1803+784	18:03:39.2	+78:27:54	2.1		
1807+698	18:07:18.5	+69:48:57	0.8		
1823+568	18:23:14.9	+56:49:18	1.0	2.3	
1828+487	18:28:13.5	+48:42:41	2.5		
1921−293	19:21:42.2	−29:20:26	10.3	7.3	
1928+738	19:28:49.3	+73:51:45	2.8		
1954+513	19:54:22.5	+51:23:46	1.1		
CYGA	19:57:44.5	+40:35:46			
1958−179	19:58:04.6	−17:57:17	2.9		
K3-50A	19:59:50.1	+33:24:19	6.5		
2005+403	20:05:59.6	+40:21:02	1.5		
2007+776	20:07:20.4	+77:43:58	1.5		
2037+511	20:37:07.5	+51:08:36	3.0		
DR21	20:37:14.3	+42:09:00	15.6		
NGC7027	21:05:09.4	+42:02:03	5.2		
2128−123	21:28:52.7	−12:20:21	1.0		
2134+004	21:34:05.2	+00:28:25	2.1		
2145+067	21:45:36.1	+06:43:41	3.5		
BLLAC	22:00:39.4	+42:02:09	1.9		
2201+315	22:01:01.4	+31:31:06	3.0		
2210−257	22:10:14.1	−25:44:23	2.1		

Table 4.1: Galactic and Extragalactic Continuum Pointing Sources (continued)

Source	α(B1950)	δ(B1950)	S_ν(3mm) (Jy)	S_ν(2mm)	S_ν(1mm) (Jy)
2216−038	22:16:16.4	−03:50:41	1.2		
3C446	22:23:11.1	−05:12:18	4.0		
2230+114	22:30:07.8	+11:28:23	3.7		
2234+282	22:34:01.7	+28:13:23	1.2		
2243−123	22:43:39.8	−12:22:40	2.3		
3C454.3	22:51:29.5	+15:52:54	6.3		
2255−282	22:55:22.3	−28:14:22	2.4		
NGC7538	23:11:36.7	+61:11:50	2.1		
2318+049	23:18:12.1	+04:57:23	1.1		
CASA	23:21:11.0	+58:32:48			
2345−167	23:45:27.7	−16:47:53	2.2		

of the source.

To make a five-point map proceed as follows:

Continuum Five-Point:

1. Select an appropriate source to point on, such as a planet or other strong continuum source.
2. Using the pointing charts, make an initial guess for the azimuth and elevation pointing offsets.
3. Ask the operator to setup for a continuum five-point measurement on the chosen source. The operator will set the integration time per sample and the number of **OFF–ON–ON–OFF sequence** pairs to measure on the source. For the stronger sources, 5 seconds and 1 pair is sufficient. For the weaker sources, 10 seconds and 2 or 3 pairs may be needed. If the source is somewhat extended, ask the operator to set the grid spacing to be the semi-diameter of the source. All other parameters will default to reasonable values. Once everything is set, ask the operator to start the measurement.

Spectral Line Five-Point:

1. Select an appropriate source. The source listing in Table 4.2 is by no means all-inclusive, but if another source is used, take care that it is really suitable for use as a pointing source. In particular, it should have an angular size that is smaller than, or at least comparable to the antenna beam size and possess an accurately known position.

Table 4.2: Spectral Line Pointing Sources

				CO		HCN	SiO
Source	α(B1950)	δ(B1950)	V_{LSR}(km s^{-1})	$T_R^*(1 \to 0)$	$T_R^*(2 \to 1)$	$T_R^*(1 \to 0)$	$T_R^*(2 \to 1)$
R Scl	01:24:39.9	−32:48:05	−18.0	1	?	?	N.E.
Mira	02:16:49.0	−03:12:12	47.0	1			3 (v)
IK Tau	03:50:43.7	11:15:30	35.0	0.5			5 (v)
GL 618	04:39:33.8	36:01:15	−21.0	1			N.E.
Ori IRc2	05:32:47.0	−05:24:24	4.0				
U Ori	05:52:50.9	20:10:05	−39.0				1 (v)
GL 865	06:01:17.5	07:26:03	42.0	0.5			N.E.
VY CMa	07:20:54.7	−25:40:12	24.0				
R Leo	09:44:52.2	11:39:40	1.0	0.1			8 (v)
IRC+10216	09:45:14.8	13:30:41	−26.0	8	12		N.E.
CIT 6	10:13:11.0	30:49:17	−2.0	2	2		N.E.
V Hya	10:49:11.3	−20:59:03	−18.0	0.5			N.E.
R Hya	13:26:58.4	−23:01:23	−1.0				
W Hya	13:46:21.1	−28:07:08	40.0				
U Her	16:23:34.7	19:00:16	−14.0				1 (v)
IRC+20326	17:29:42.0	17:47:36	−5.0	0.5			N.E.
VX Sgr	18:05:03.2	−22:14:06	6.0				10.0
IRC+20370	18:39:41.7	17:38:16	−1.0	0.8	1		N.E.
W Aql	19:12:41.6	−07:08:08	−25.0	1.0			N.E.
χ Cyg	19:48:38.5	32:47:11	10.0	0.7	1.5		5 (v)
V Cyg	20:39:41.3	47:57:44	13.0	1	1		N.E.
NML Cyg	20:44:33.8	39:55:57	0.0				

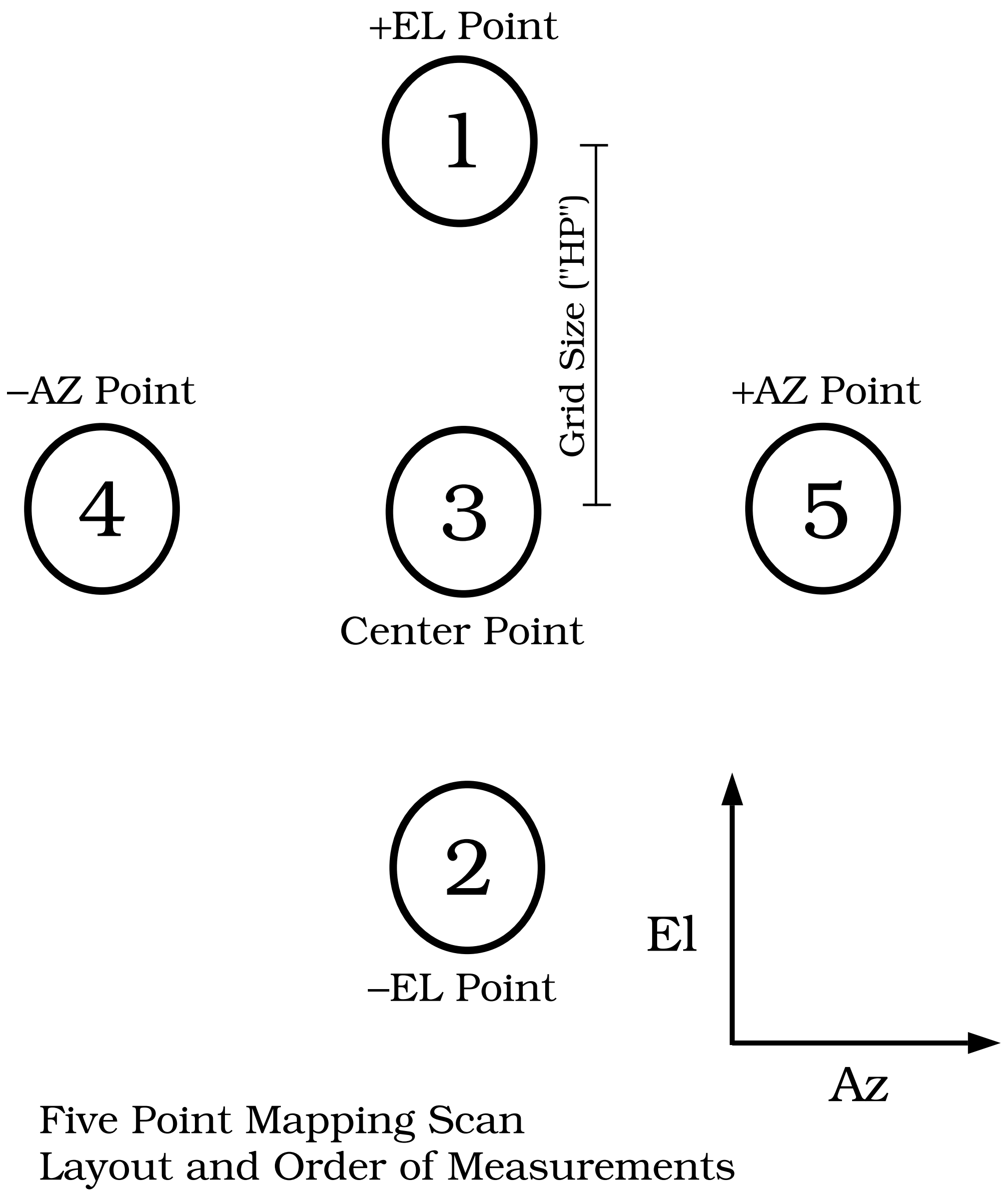

Figure 4.4: Five point mapping scan sequence.

2. Ask the operator to setup for a spectral line five-point measurement on the chosen source. Set the integration time per sample, the number of ON/OFF pairs to measure on the source, the number of scans per calibrate, and for a total power five-point the ON and OFF integration time. Depending on the source size, you may also have to set the grid spacing appropriately. All other parameters will default to reasonable values.
3. Choose an azimuth offset angle for the reference, to be used for position switching.
4. Using the pointing charts, make an initial guess for the azimuth and elevation pointing offsets.
5. Ask the operator to start the measurement.

To process these measurements, there are a number of *condar* and *line* procedures available.

4.6.1.1 Continuum Five-Point Analysis

Continuum five-point measurements are processed automatically by the on-line dataserver. The results from these on-line fits are sent automatically to the operator for entry into the control system. To process a continuum five-point measurement manually, use the *condar* resident procedure *five*, which can be abbreviated as *f*. You can look at the results for each channel separately by using the command

```
Condar > scan_number f
```

Channel 1 is selected by specifying subscan number .01, while channel 2 is selected with subscan .02. The display (Figure 4.5) provides the observer with the best-fit positional offsets in azimuth and elevation, along with the estimated peak flux density of the source, both for a constrained fit of Gaussian half-width HP and an unconstrained solution. The optimum pointing offsets (labeled CORRECTED OFFSETS) are also printed, assuming the given position of the source to be correct.

4.6.1.2 Spectral Line Five-Point Analysis

The display of the map and the fit for pointing offsets is somewhat more involved than for a continuum five point. There is a standard *line* procedure which processes all types of spectral line five-point measurements. To process a measurement, within *line* type:

```
Line> center_scan_number fivel1 (for channel 1)
Line> center_scan_number fivel2 (for channel 2)
```

You will be asked some questions by the routine:

`AVERAGE THE TWO RECEIVERS? (1=YES, 0=NO)` – This question is asked only if the data were taken in *series* mode. If the question is answered “yes”, the routine averages the first and second filter bank to improve sensitivity. You should answer “yes” only if you are reducing the first filter bank; you will usually not need to reduce the two filter banks separately if averaging the two. If the data were taken in *parallel* mode, the two polarization channels in each filter bank are automatically averaged.

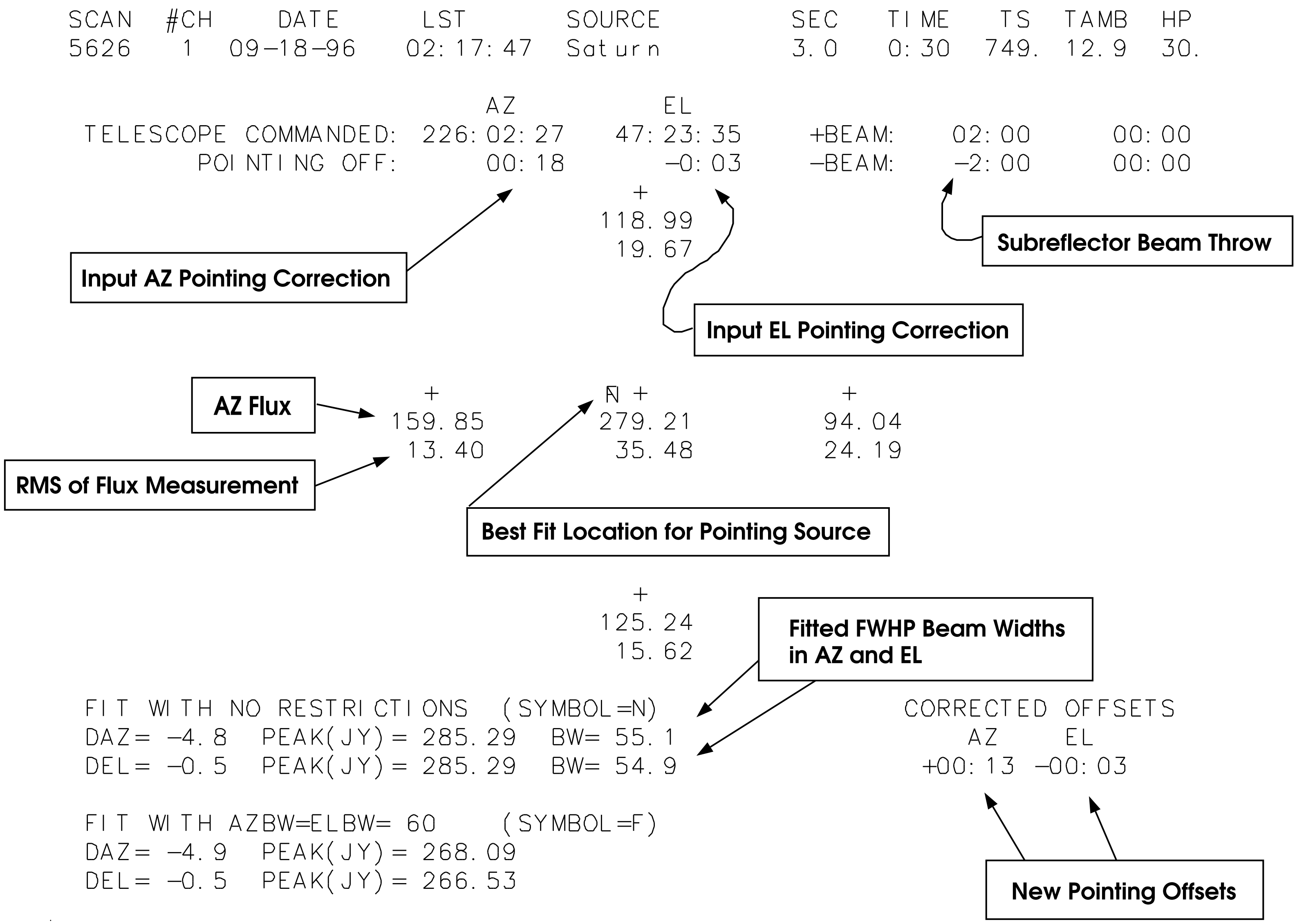

Figure 4.5: Continuum Five-Point Analysis Example

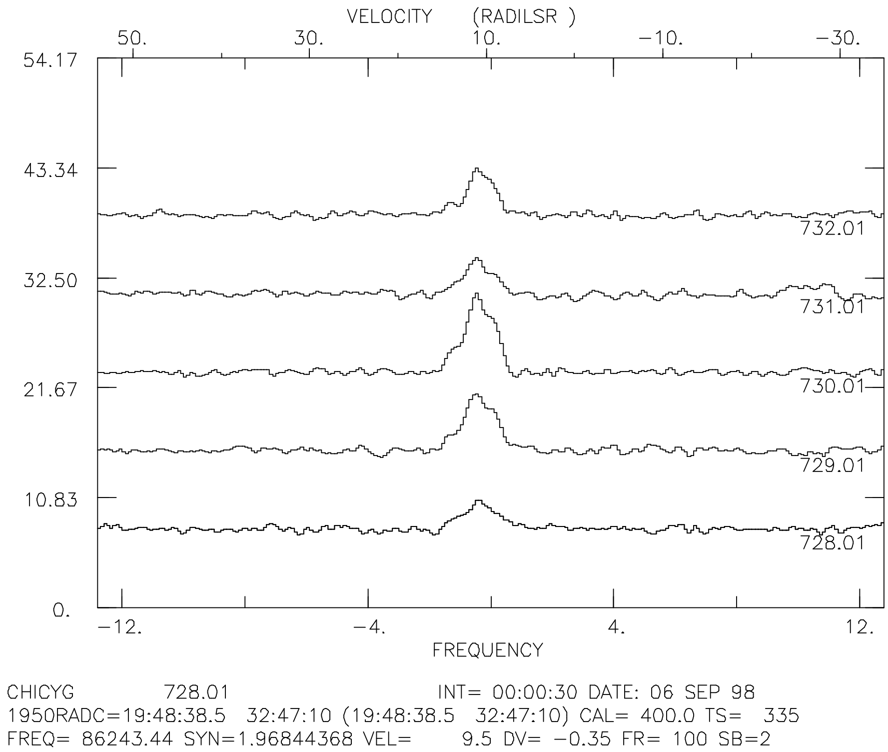

Figure 4.6: Display of each scan produced by the *line* procedure *fivel*.

`USE OLD BASELINE & INTEG. REGIONS? (1=YES, 0=NO)` – The observer must define baseline fitting and spectral line integration regions for this routine. If these regions have already been accurately set, as, for example, in a five-point of the same source performed immediately prior to the present one, you can answer "yes" and speed up the reduction process considerably. If you answer "no", the spectrum at the center of the map is displayed on the screen, and the question `ENTER # OF BL SEGS` is printed. This part of the *f* routine is the same as the *bset* procedure. The observer must enter the number of baseline segments to be used to fit a least-squares baseline. [NOTE: The order of the fit is determined by whatever *nfit* is set to (the default is 1 – see the *line* data reduction manual for a description of the baseline fitting facilities).] When the number of segments to be fit is entered, the graphics crosshairs appear and you must mark off the two ends of each segment with the crosshairs (move the crosshairs to the desired position and strike any mouse button). When this operation is finished, the baseline is removed from the center spectrum and the spectrum is replotted. The prompt `ENTER INTEG. REGIONS` is printed and the crosshairs reappear. You should then mark off the two velocity/frequency extremities of the spectral line (or whatever region you wish to integrate over).

`DISPLAY EACH SCAN? (1=YES, 0=NO)` – If you answer "no", the map and the fit for new offsets are printed out. If you answer "yes" each scan of the map, with baselines removed, is displayed on a single plot, one spectrum on top of the other (see Figure 4.6).

`TYPE 1 TO CONTINUE OR 0 TO STOP` – If you approve of the fits, answer 1 and the map and fit for new offsets will be displayed. An example of the five-point map with explanatory annotations is given in Figure 4.7.

4.6.2 Pointing Model Equations

In addition to coordinate conversions, the telescope tracking program incorporates pointing corrections. The pointing corrections take into account resolver zero offsets, differences between electrical and mechanical axes, axis tilt, etc. The coefficients of the pointing model equations are determined during dedicated optical and radio pointing source measurements several times during the observing season. The pointing models used for the 12m are described in detail in Appendix A.

4.6.3 Pointing Data Analysis Program

Each time a continuum five-point measurement is made, the on-line data server performs a fit to the results and writes them to a permanent file for later analysis. A program called *gpoint* is available on any of the mountain workstations for display and analysis of the recent pointing history of the telescope.

To start the program, type *gpoint* from any login prompt. *gpoint* is menu-driven, so you need only select the appropriate entries in each menu to configure the data selection and display parameters to suit your needs. An example of a *gpoint* plot is given in Figure 4.8.

4.7 Focus

4.7.1 Axial Focus

To bring the incident radiation to a focus at the receiver feed horn, the subreflector of the 12m may be moved in and out along the electrical axis of the telescope. The focus exhibits an elevation dependence which is automatically corrected by the control system computer, according to the equation

$$F(E) = F_0 + 2.8\sin(E) \tag{4.1}$$

where $F(E)$ is the focus setting in millimeters, E is the elevation, and F_0, the subreflector focus setting at 0° elevation, is to be determined by the observer. F_0 is given in millimeters, and larger values of F_0 represent greater distances between the dish surface and the subreflector.

An automatic procedure called a *focalize* (this word really is in the dictionary!) will determine the best value for F_0. An analysis routine of the same name exists in *condar* and *line* for displaying and fitting the results. Instructions for performing a *focalize* are given in §4.7.2.

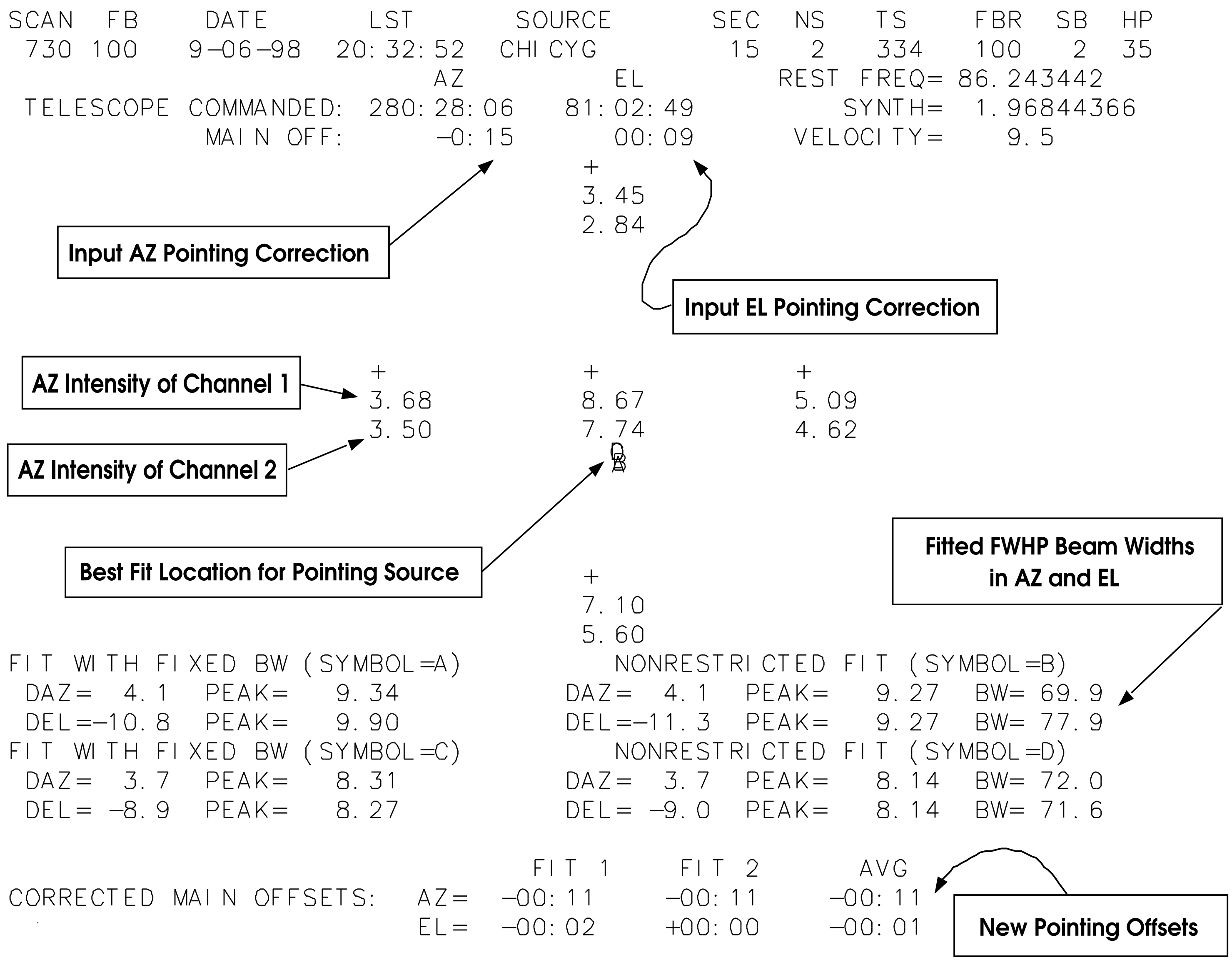

Figure 4.7: Spectral line five-point analysis example.

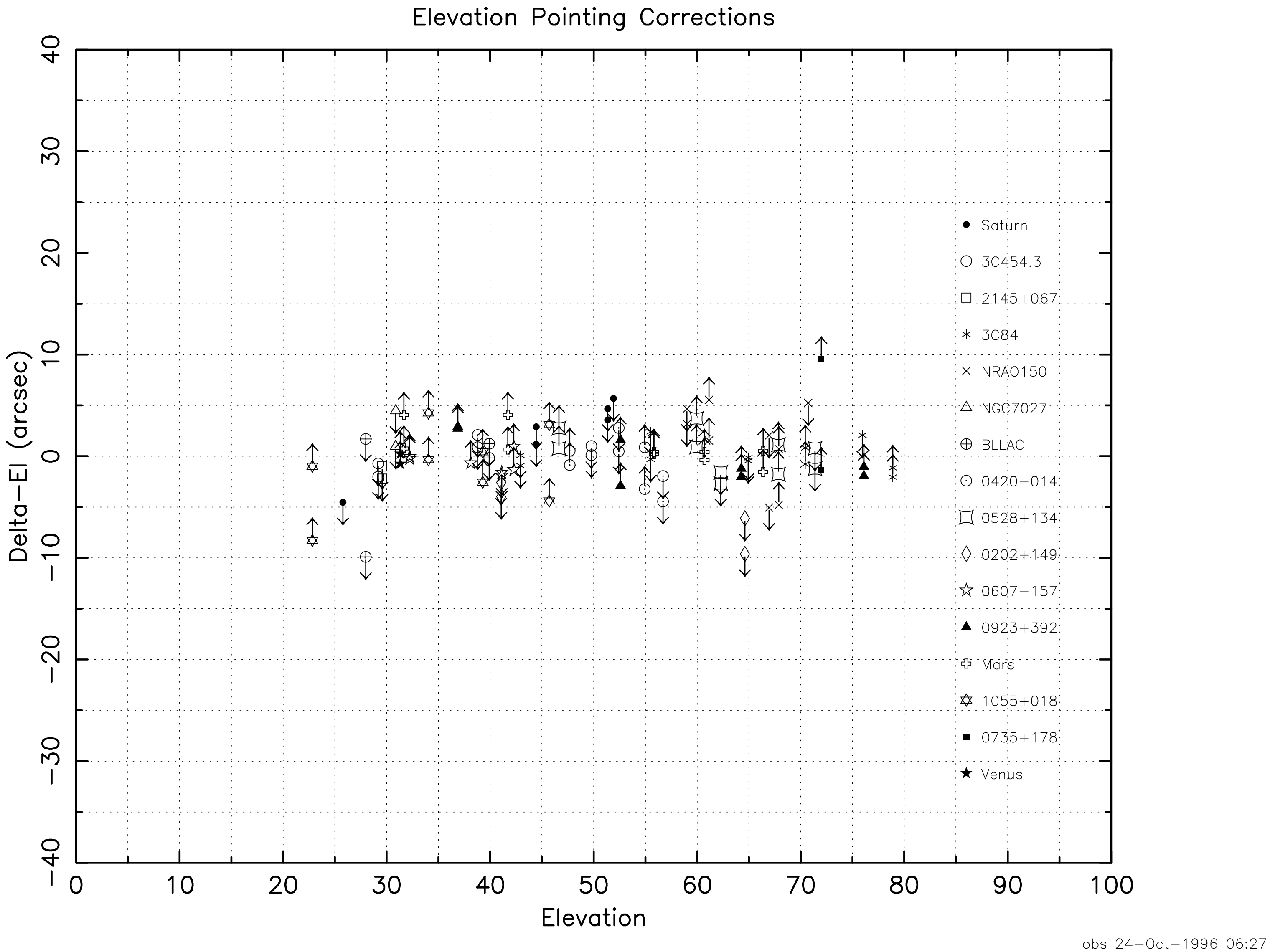

Figure 4.8: GPOINT display example. Each pointing source is indicated by a unique symbol, while the arrow on each symbol indicates whether the source was rising or setting.

4.7.2 Determining the Axial Focus

The axial focus of the telescope should be checked occasionally during an observing run. It is often most convenient to make a focus check after a continuum five-point pointing measurement since both measurements use the same kinds of sources (strong continuum point sources). It is particularly important to check the focus after nightfall and daybreak. Focusing is performed via the *focalize* procedure. This steps the radial distance of the subreflector from the telescope vertex through seven positions centered on the nominal best setting (F0). Larger values of F0 represent greater distances between the dish surface and the subreflector. The incremental movement between positions (WL) is set to half of the observing wavelength by default, but can be set by the observer.

Perform a *focalize* as follows:

1. Choose as bright a continuum source as possible. The planets Jupiter, Venus and Saturn are ideal. If the source is extended relative to the telescope main beam, the accuracy of the *focalize* will be diminished, however.

2. Make a five-point map of the source to optimize the antenna pointing (see §4.6.1).

3. Reasonable default values for the axial subreflector position (F0) have been assigned to each receiver, but, if you find it necessary you can give the operator a value for F0.

4. The default integration time per sample is 5 seconds, but if you are performing a *focalize* measurement on a weak source, you may need to increase this to 10 – 15 seconds.

5. If you are satisfied with the setup, ask the operator to start the measurement.

Focalize measurements are processed automatically by the on-line dataserver, the results of which are sent automatically to the operator for entry into the control system. To reduce the *focalize* in *condar* use the commands,

```
Condar > scan_number focalize
```

where each channel is selected by specifying either subscan .01 for channel 1 or .02 for channel 2. The output from the *focalize* procedure is shown in Figure 4.9. The fit should be smooth and "quasi-Gaussian". (If not, repeat the *focalize*. Increase the value of WL if you think this is necessary.) The display will give a best-fit value for F0. Where appropriate, you should average the values for the two channels.

4.7.3 Lateral Focus

The position of the subreflector for optimum gain shifts in the elevation direction, with changing elevation angle. The change in antenna gain produced by this effect is not significant at 3mm wavelengths but could be as much as 20% or more at 1.3mm and shorter wavelengths. The 12m is equipped with lateral "north-south" and "east-west" translation stages at the prime focus to eliminate this loss in antenna gain. The computer is able to automatically control the positioning of these stages, simultaneously applying

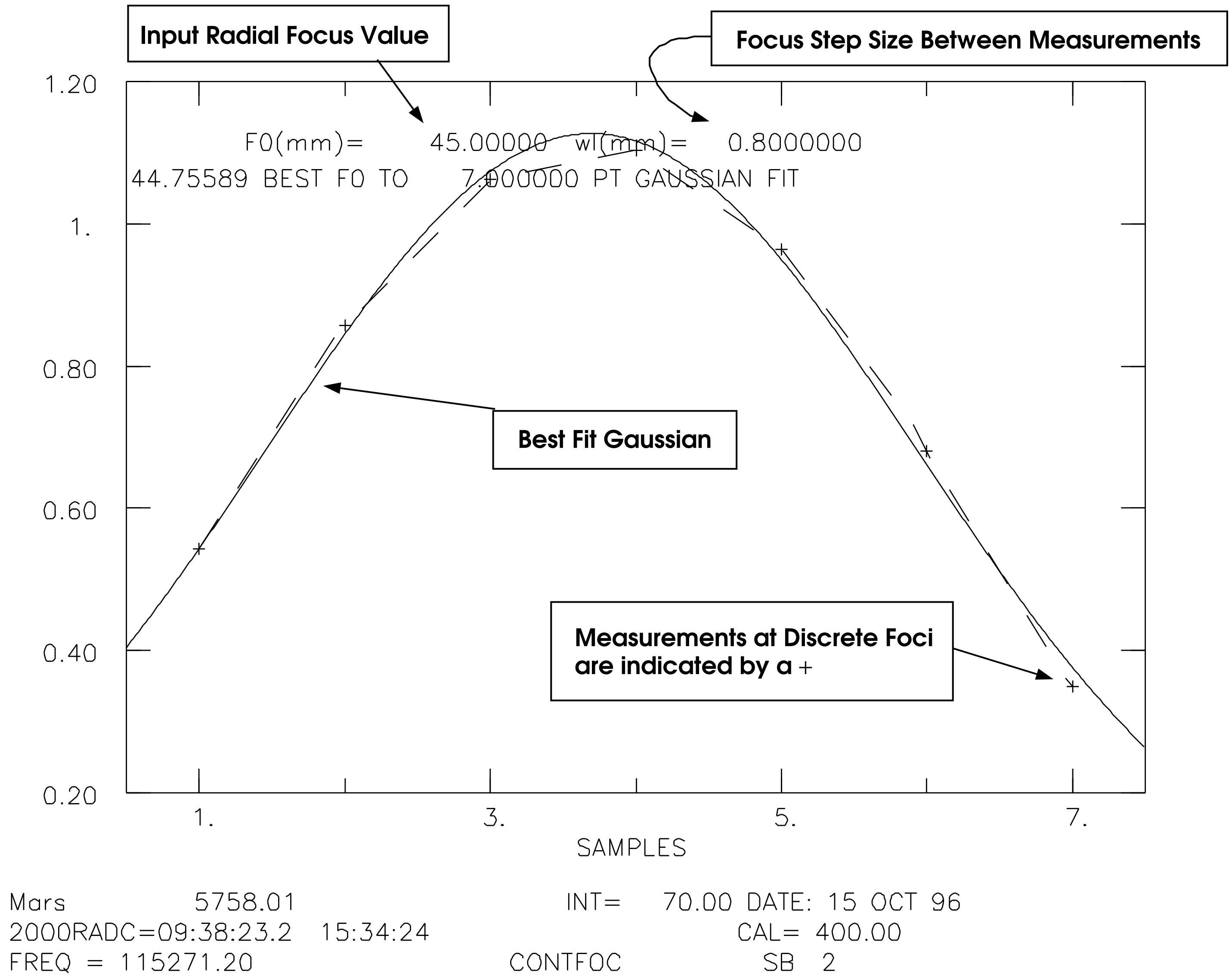

Figure 4.9: Focalize display example.

an appropriate correction to the telescope pointing in elevation and azimuth, respectively. This correction to elevation pointing is $31.5''/\mathrm{mm}$ (which is the prime focus "plate scale" derived in Appendix G) of movement in the north-south focus or east-west focus stages.

In the future, the coefficients necessary to control the movement of the north-south and east-west translation stages will be installed in the computer and applied automatically. At this time, the north-south and east-west translation stages can be set to a given position, but are usually left fixed in this position. Automatic procedures for fitting for maximum north-south or east-west gain, called *nsfocal* and *ewfocal* are available. These routines operate analogously to the *focalize* procedure. Normally, only staff astronomers use these procedures; we do not recommend that observers spend time trying to optimize this further.

Chapter 5

Spectral Line Observing

5.1 Startup Checklist

Once the scientific goals of the observing session are clearly in mind, you must decide upon the equipment and observing techniques to be used. The decisions to be made and the options are listed below.

Sideband Choice: For double sideband observations, care must be taken in choosing the placement of the image sideband.

Spectrometer Configuration: Filter bank spectrometers with several different resolutions are available. The observer must choose which to use and how they should be configured (the **parallel** or **series** option). The Millimeter Autocorrelator (MAC) , which has numerous resolution and bandwidth options, is also available.

Observing Mode: Choices are

- Total Power Scans – ON and OFF total power spectra are recorded separately for later processing into final spectra. The observer may take several ON scans for each OFF.
- Position Switching – The telescope moves between an offset, or OFF, position (in relative or absolute coordinates) and a source, or ON, position. The spectrum is recorded as a ratio of (ON – OFF)/OFF.
- Frequency Switching – The local oscillator is shifted by several MHz at a rate of 1.25, 2.5, or 5.0 Hz. The spectrum is recorded as a ratio of (SIG – REF)/REF.
- Beam Switching plus Position Switching – The subreflector is chopped at a rate of 1.25 to 5.0 Hz, and the telescope is repositioned at a prescribed rate (typically every 30-90 seconds). The spectrum is recorded as (ON – OFF).
- Grid Mapping – Total power or absolute position or frequency switched data are acquired while the telescope moves to user-specified spatial positions.
- On The Fly Mapping – Total power data are acquired every 0.1 seconds while the telescope is driven continuously over a specified map field.

Observing Time Budget: Prior to the start of observations, you should make a rough budget of observing time requirements. In addition to the integration time on the program sources, you should allow time for "overhead" items such as telescope movement, and pointing and calibration tests.

Before beginning program observations, check the telescope pointing and focus. A few observations of test sources are also advisable. These observations are discussed in Chapters 2, 4, and 6.

5.2 Sideband Choice

All of the 12m receivers operate by default in a single sideband (SSB) mode and require upper sideband (USB) operation. For the 2 and 3mm receivers, it is possible to observe DSB. Equipment constraints, such as the tuning range of the local oscillator or the receiver, may sometimes determine the sideband used in DSB mode. Other times, the presence of telluric lines steer the choice (see Figure 6.1). When using DSB mode, make the sideband choice with care.

The primary things to watch out for when choosing the sideband configuration for a DSB measurement is the presence of "contaminating" lines from the image sideband. Consult a good tabulation of spectral lines such as the Lovas Catalog (F. J. Lovas, J. Phys. Chem. Ref. Data, 15, 251, 1986) to see what spectral lines are present in both the signal and image sidebands. If an image line is too close to the program line in the signal sideband, a small local oscillator shift will usually cure the problem (the frequency axes run oppositely for the upper and lower sidebands). One can also make small adjustments in the IF to change the placement of lines from the two sidebands. Sometimes, lines from the image sideband can be used to advantage for calibrations or system checks.

With a slight rearrangement of Equation 3.4, we can write the expression for the sky frequency as a function of the LO frequency settings

$$f_{sky} = m\,(N f_{syn} + f_{lock}) - j f_{IF} \tag{5.1}$$

where f_{syn} is the synthesizer frequency, f_{sky} is the sky frequency of the emission (the rest frequency with Doppler corrections), j = +1 for lower sideband and −1 for upper sideband, f_{IF} is the IF frequency (1.5 GHz by default), m is the factor by which the LO frequency is multiplied before injection into the mixer, f_{lock} is the the phase lock loop offset frequency (100 MHz), and N is the synthesizer harmonic. The Doppler correction is determined by the choice of velocity type (see Chapter 4).

$$f_{sky}(RAD) = f_{rest}\left(1 - \frac{v_{object} + v_{antenna}}{c}\right) \tag{5.2}$$

$$f_{sky}(OPT) = \frac{f_{rest}}{1 + \frac{v_{object}+v_{antenna}}{c}} \tag{5.3}$$

$$f_{sky}(REL) = f_{rest}\sqrt{\frac{1 - \frac{v_{object}+v_{antenna}}{c}}{1 + \frac{v_{object}+v_{antenna}}{c}}} \tag{5.4}$$

where v_{object} and $v_{antenna}$ are the object and antenna velocities relative to the local standard of rest and c is the speed of light.

5.3 Spectrometers

Two spectrometer systems are available at the 12m: a suite of analog filter banks and a Millimeter Autocorrelator (MAC), which is a digital correlation spectrometer.

5.3.1 Filter Banks

Most of the analog filter banks have 256 channels each. The filters are integrated, multiplexed, and recorded by the control computer every 100 milliseconds. A total of 512 channels can be recorded at a time, which means that two filter banks can be used for each scan. The filter spectrometers available and the ways in which they can be configured are described below. Table 5.1 lists the characteristics of the 12m filter banks

5.3.1.1 The Parallel/Series Option

Most of the 256 channel filter banks can be split into two 128 channel sections that can be fed with independent IF signals. When a filter bank is split into two sections, the bank is said to be in a **parallel** configuration. Each polarization channel of the receiver feeds half of a filter bank in this configuration. The advantage of this mode is that the two halves of the filter bank can be averaged to produce improved signal-to-noise in the final spectrum. The disadvantage of this mode is that the total bandwidth is cut in half. Observers of narrow Galactic lines typically choose the parallel option, and use two filter banks with different resolutions.

Observations that require larger bandwidths, such as CO from other galaxies, usually choose the **series** mode. In the **series** mode, the two filter bank halves are used end-to-end to analyze a single input IF signal. A typical observing mode might be to use one of the 1 MHz filter banks for polarization 1 and the other for polarization 2. The two banks can be averaged in software to improve the signal-to-noise of the final spectrum. Figure 5.1 is a diagram showing how the **parallel/series** option works.

5.3.1.2 Bad Channel Elimination

At times, certain channels in the filter banks are defective. You can identify these "bad" channels by examining the output of a vane calibration cycle, which is called the *gains*. Vane calibration is described in detail in §5.6.1. Bad filter channels usually appear as spikes in the **gains** and will often cause scaling problems in the final spectrum if not eliminated. You can display the **gains** with the *line* data reduction program. To find the bad channels, perform a calibration scan and type `g1` to display the first filter bank and `g2` to display the second bank. If bad channels exist, type the command `badch`. You will be asked to enter the number of bad channels. After doing so, the crosshairs will appear on the screen. Move the vertical crosshair to each bad channel and select any mouse button. When all the bad channels have been entered, the program will give a report of the channel numbers.

Table 5.1: 12m Filter Bank Characteristics

Filter Resolution[a]	Channels per Bank	Filter Banks Available	Parallel/Series Option	Hardware Center Channel (Par/Ser)
2 MHz	256	2	yes	64.5/128.5
1 MHz	256	2	yes	64.5/128.5
500 kHz	256	1	yes	64.5/128.5
250 kHz	256	1	yes	64.5/128.5
100 kHz	256	1	yes	64.5/128.5
30 kHz	128	1	no	65

[a]**NOTE:** This is the FWHM channel width. See Appendix D for further details.

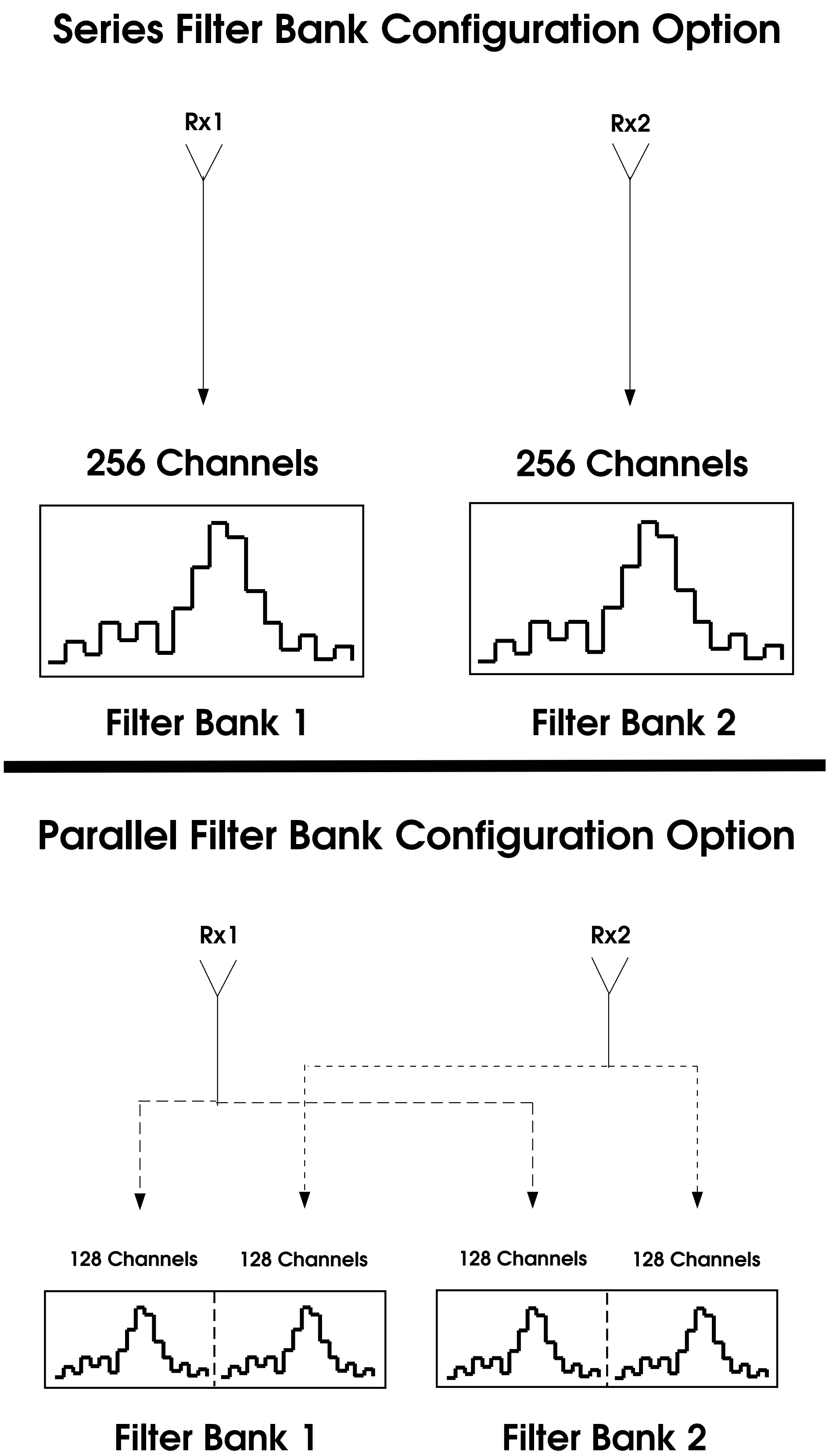

Figure 5.1: The filter bank parallel and series configurations.

Give these numbers to the operator. Up to 16 bad channels can be eliminated, but rarely more than 5 channels out of 512 will be bad. It is also possible to eliminate blocks of 16 channels, but this is seldom necessary. If blocks of 16 channels are bad, notify the Friend of the Telescope.

Once the operator has entered the bad channels, he will perform another vane calibration cycle to set the bad channels to 1.0×10^{-20}, which is the flagged channel value. On all subsequent spectra, those channels will be flagged. These bad channels can be eliminated in reduction software by using the `replace` command (see the *line* manual).

5.3.1.3 Frequency Offsets

Given the broad-band tunability of the 12m receivers, one can shift the rest frequency measured by the filter banks by specifying a frequency offset to be added to the rest frequency. Offsets as large as the entire bandwidth of the receiver ($\pm$300 MHz) are possible. Filter bank offsetting is most often used in conjunction with the 4IF Millimeter Autocorrelator (MAC) mode (see §5.3.2.1 for further information).

5.3.2 Millimeter Autocorrelator

The Millimeter Autocorrelator (MAC) offers a number of bandwidth and resolution modes, listed in Table 5.2. Most general single-beam dual-polarization measurements are done using the configurations with 2 IF's. The 8 IF modes are designed for use with the 1mm Array receiver. The 4IF Millimeter Autocorrelator (MAC) mode is a special-purpose observing mode allowing the measurement of two frequencies each at two polarizations simultaneously.

5.3.2.1 The 4IF Observing Mode

One of the more efficient observing modes available at the 12m involves the use of the 4IF configuration of the Millimeter Autocorrelator (MAC) in conjunction with the frequency offsetting capabilities of the filter banks. Within the IF modules which feed the receiver signals to the Millimeter Autocorrelator (MAC) there are oscillators which can shift the input receiver signals by $\pm$300 MHz in 5 MHz steps. Since these oscillators are independent of the Fluke synthesizers which provide the frequency offsetting capabilities of the filter banks, it is possible to measure spectra at three separate frequencies within the 600 MHz bandwidth of the receiver (assuming both mixers are tuned to the same frequency). A graphical description of this mode is shown in Figure 5.2.

To given a practical example, say I want to simultaneously measure the H_2CO emission from the $3_{03} \rightarrow 2_{02}$ and $3_{22} \rightarrow 2_{21}$ transitions at 218222.192 and 218475.632 MHz, respectively. These two frequencies are separated by 253.440 MHz, which would restrict my choice of backends to the 2MHz filter banks in parallel and the 600 MHz Millimeter Autocorrelator (MAC) mode. Since I want to look at galactic sources with narrow lines, this wide-band modes are not acceptable. To use the 4IF mode to measure both transitions simultaneously, I would

Table 5.2: Millimeter Autocorrelator (MAC) Configurations

Bandwidth and Channels		Useable Bandwidth and Channels[1]		$\Delta\nu^2$	Resolution
(MHz)	Channels	(MHz)	Channels	(kHz)	(kHz)
2 IF Modes					
800	2048	600*	1536	390.6	781.2
800	4096	600	3072	195.3	390.6
400	4096	300*	3072	97.6	195.3
400	8192	300	6144	48.8	97.6
200	8192	150*	6144	24.4	48.8
200	16384	150	12288	12.2	24.4
100	16384	75*	12288	6.1	12.2
100	32768	75	24576	3.0	6.1
4 IF Modes					
800	1024	600*	768	781.2	1562.0
800	2048	600	1536	390.6	781.2
400	2048	300*	1536	195.3	390.6
400	4096	300	3072	97.6	195.3
200	4096	150*	3072	48.8	97.6
200	8192	150	6144	24.4	48.8
100	8192	75*	6144	12.2	24.4
100	16384	75	12288	6.1	12.2
8 IF Modes					
800	512	600*	384	1562.5	3125.0
800	1024	600	768	781.2	1562.0
400	1024	300*	768	390.6	781.2
400	2048	300	1536	195.3	390.6
200	2048	150*	1536	97.6	195.3
200	4096	150	3072	48.8	97.6
100	4096	75*	3072	24.4	48.8
100	8192	75	6144	12.2	24.4

[1] The useable bandwidth takes account of the 75% efficiency of the analog filters.

[2] **NOTE:** This is the frequency sampling interval, not the FWHM channel width, for a given channel. The FWHM channel width is 2.0 times this value. See Appendix D for details.

All values in this table refer to each IF.

Modes tagged with a $*$ are produced by dropping the last half of the lags.

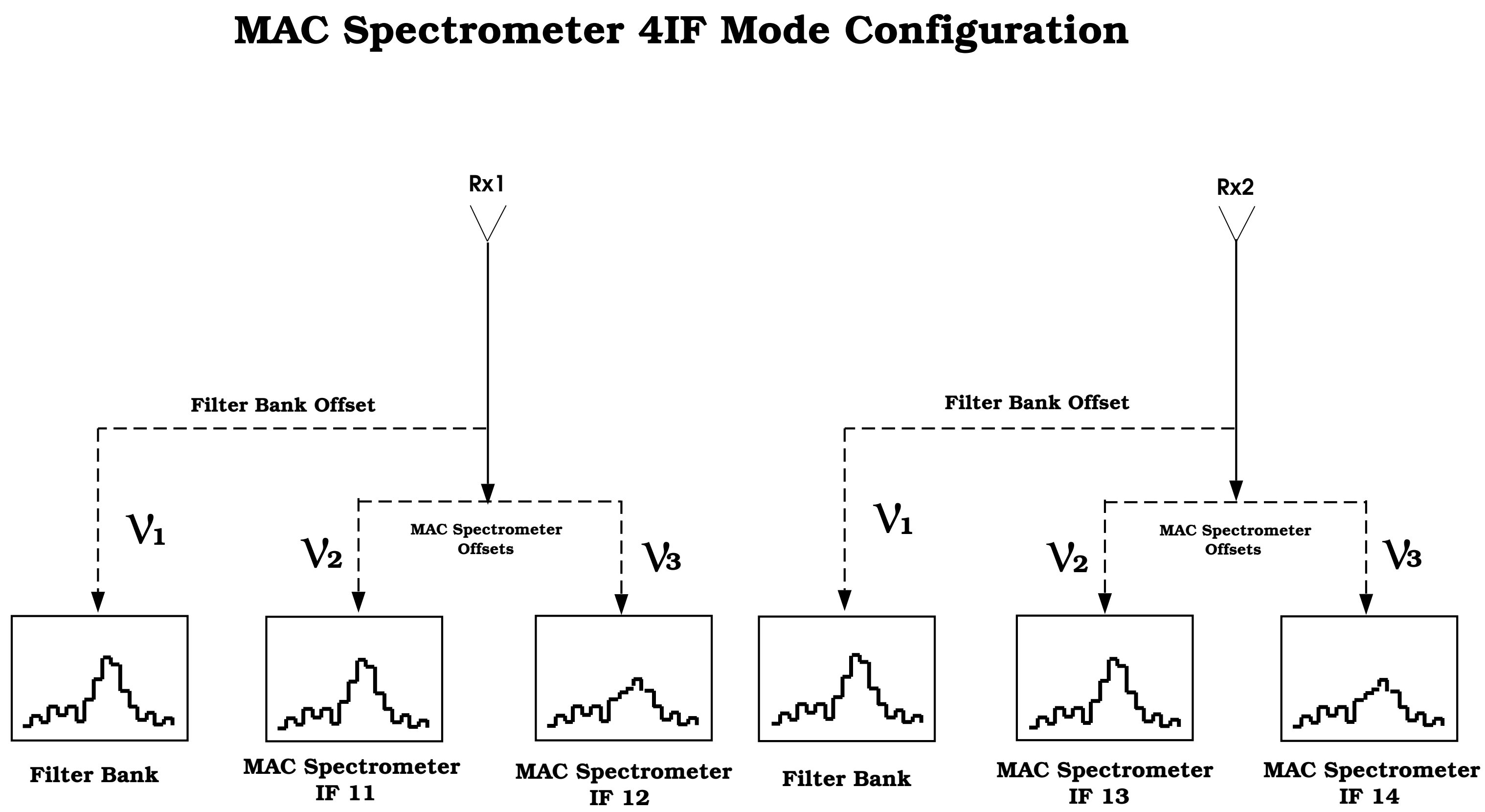

Figure 5.2: Millimeter Autocorrelator (MAC) 4IF mode configuration.

1. Tune the receiver to a frequency midway between the two rest frequencies, which in this case is 218348.912 MHz.

2. Set the filter bank offset so that I can measure the $3_{03} \rightarrow 2_{02}$ transition, which would be $218348.912 - 218222.192 = 126.720$ MHz.

3. Set the two Millimeter Autocorrelator (MAC) offsets so that IF's 11 and 13 receive the $3_{03} \rightarrow 2_{02}$ transition and IF's 12 and 14 receive the $3_{22} \rightarrow 2_{21}$ transition. Since the Millimeter Autocorrelator (MAC) offsets must be in 5 MHz steps, I would set these offsets to ∓ 125 MHz. The center frequency for IF's 11 and 13 would then be $218348.912 - 125.0 = 218223.912$ MHz, while the center frequency for IF's 12 and 14 would be $218348.912 + 125.0 = 218473.912$ MHz.

5.4 Observing Modes

There are six primary spectral line observing modes are available at the 12m. The attributes and applications of each are described in detail below. Signal processing and calibration for each mode are described in §5.6.

5.4.1 Total Power ONs and OFFs

Two observing procedures, called **tpon** and **tpoff**, are available for recording total power spectral line scans. The two procedures are identical, except that **tpon** tracks the ON (source) position and **tpoff** tracks the OFF (reference) position. You must execute the procedures manually, one scan at a time. As such, these procedures are mainly used for diagnostic purposes. To use **tpoff** and **tpon**, follow this prescription:

- Provide the operator with the following setup information:

    1. The source catalog and the source name (the ON position).
    2. The (AZ,EL) pointing corrections and the reference offset position (OFF). The offset may be specified in AZ and EL or in RA and DEC.
    3. The integration time of the scan in seconds (the scan will have only one **sample**, i.e., **repeats** does not apply to TPN or TPF scans).

- Have the operator perform a vane CALIBRATE, a TPF (the OFF scan), and a TPN (the ON scan) in that order. The scan numbers of the CALIBRATE and TPF will be stored in the header of the TPN scan for use in data processing.

- To look at either the TPF or TPN scans, type

  ```
  Line> scan# f
  Line> scan# s
  ```

  to choose either the first or second filter bank, respectively. The displayed scan will be a total power bandpass. Unless the band contains a very strong spectral line, you will probably not be able to see any lines. To display a final spectrum, formed from the ratio (ON–OFF)/OFF * CAL, type

```
Line> install ton
```

```
Line> scan# ton
```

(Note that you only need to `install` the procedure once per session). The `ton` procedure will use the last CALIBRATE and TPF scan to form the spectrum.

5.4.2 Position Switching

Position switching, called the PS mode, is the most common and reliable observing mode at the 12m for general spectral line observations. It involves considerable overhead in telescope movement and requires that equal time be spent in the ON and OFF source positions, but the data quality is usually good. In this mode, the telescope moves between the ON position and a relative OFF position, which may be specified in either azimuth and elevation, or right ascension and declination offsets. Usually the offset is in azimuth, so that the ON and OFF positions are taken at about the same airmass. The best rejection of the atmosphere and the best spectral baselines are achieved with small angular switches. Choose the smallest switch possible, so long as you are confident that the OFF position is free of source emission.

PS data recorded on disk is a final spectrum formed from the ratio (ON–OFF)/OFF, where the ON and OFF data are total power samples. In contrast to the total power observing modes **TPON** and **TPOFF**, the ON and OFF samples are not saved as separate scans for independent processing. Although the PS mode offers less flexibility in processing data than do the total power modes, it also reduces the total volume of data and makes processing easier.

To reduce telescope movement and provide the best compensation for polynomial drifts in atmospheric emission, choose the number of OFF–ON pairs to be a multiple of 2. The observing cycle will then be repeats of an OFF–ON–ON–OFF pattern characterized by a Walsh function (see Appendix E). Each ON or OFF is called a **sample** and each OFF–ON pair is called a **repeat**. The observer must tell the operator how long to integrate for each **sample** (the default is 30 seconds) and how many **repeats** per scan, or alternatively, the total length of the scan in minutes. A typical scan might be 6 minutes long, with 30 second **sample**s (meaning 6 **repeats**). You can, of course, vary the length of the scan to suit your own needs. Each ON–OFF pair can be edited individually with the *line* program (see Record Editing in the supplement to the *line* manual). The operator can issue the command to take scans one at a time, or can set the system into an automatic data-taking loop. Figure 5.3 shows an example of a spectrum produced by a PS scan.

The parameters of a PS scan that you must give to the operator are

- The relative offset position, which may be specified in either (AZ, EL) or (RA, DEC) coordinates.

- The integration time for an individual sample (ON or OFF). 30 seconds is the default.

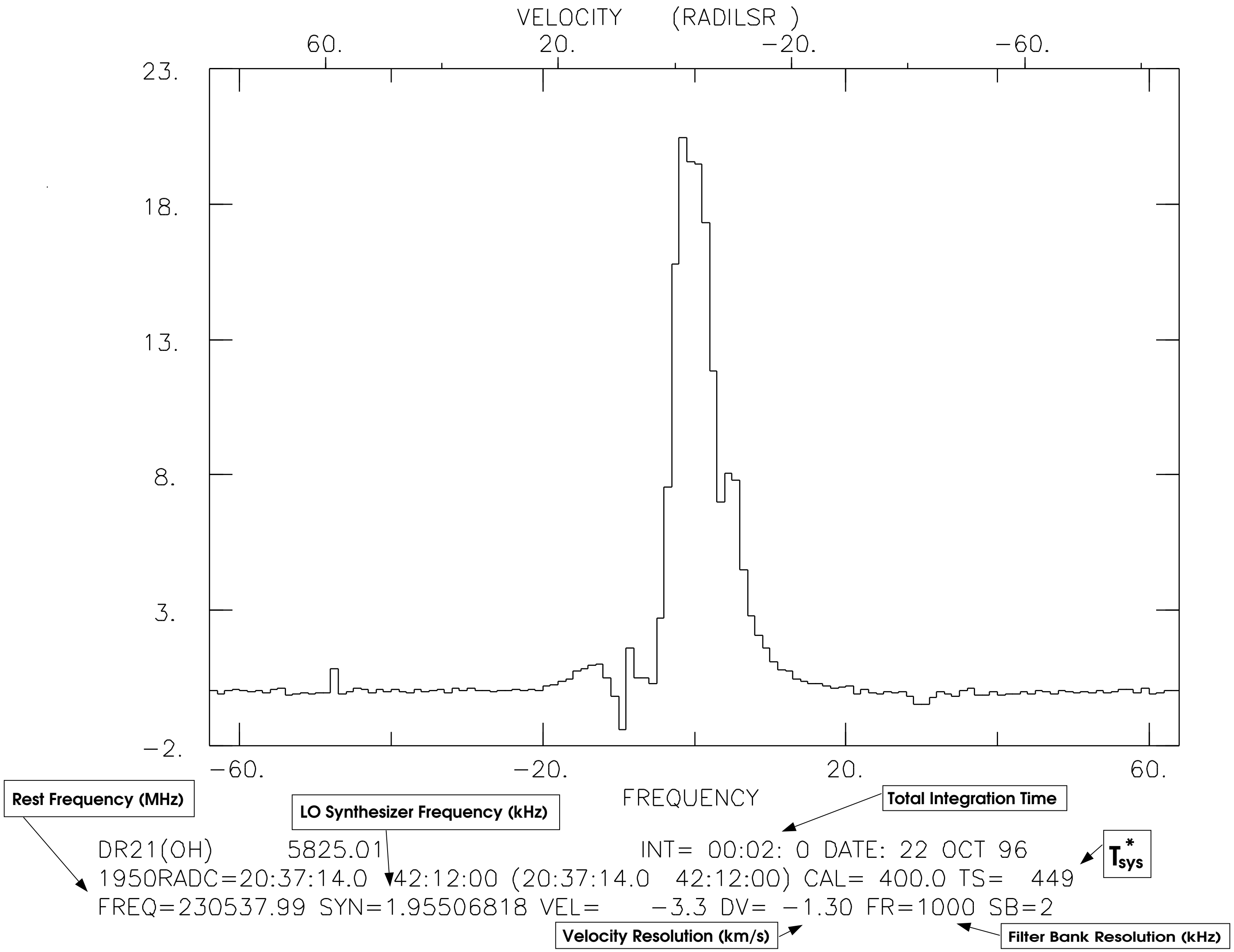

Figure 5.3: Position switched spectral line scan analyzed in the unipops program.

- The number of ON/OFF pairs (**repeats**) per scan (can be specified to the operator as the total length of the scan).

- The number of scans to be performed for every calibration measurement.

5.4.3 Absolute Position Switching

Absolute position switching, called the APS mode, is useful when observing in complex emission regions where it is difficult to find an emission-free reference position. In such cases, position switching with (AZ,EL) offsets can be dangerous because rotation of the parallactic angle as the source is tracked across the sky may cause emission to rotate into the reference beam. You will want to search for an emission-free position as close to the source position as possible, and use this as the reference position. If you wish, you can compute the (RA,DEC) offsets to this position and use ordinary position switching. Most observers find it most convenient, particularly for future observations, to enter the absolute (RA,DEC) coordinates of the reference position and use the absolute position switching observing mode.

APS is identical to ordinary position switching except that the switching is done between two positions absolutely specified by their celestial coordinates. The reference (OFF) position should be given a different name from the signal (ON) position and is best placed in a different source catalog from the signal position. Data taking and calibration options are the same as for ordinary position switching.

The parameters of an APS scan that you must give to the operator are

- The name of the source (ON) position and catalog which contains it;

- The name of the reference (OFF) position and its catalog;

- The integration time for each **sample** (ON or OFF). 30 seconds is the default;

- The number of **repeats** of an ON–OFF pair or the total integration time of the scan;

- The number of scans between each vane calibration, if that calibration method is chosen.

5.4.4 Frequency Switching

The frequency switching observing mode has two primary uses: to increase the on-source integration time through "in-band" switching and to alleviate the problem of finding an emission-free reference position when observing in a (spatially) complex emission region. It also entails less system overhead than most other observing modes. In this mode, called an FS observation, a reference spectrum is obtained by shifting the center frequency of the signal spectrum. In principle, this can be done by switching the frequency of the LO or an IF oscillator; at the 12m, the former is generally used. If the frequency shift is small enough, the spectral line will appear in both the signal and reference spectra. When the resultant spectrum is formed, the line will appear twice, once in emission and once in absorption. The spectrum can be "folded" to obtain a $\sqrt{2}$ improvement in signal-to-noise. With this technique, which is called "in-band" or "overlapped" frequency switching, you are effectively observing on-source all the time. Figure 5.4 shows an example of a spectrum produced by a FS scan.

The primary drawback of frequency switching is that the spectral baselines are generally not as good (*i.e.* flat) as with position or beam switching. This is because the two frequency positions each have their own spectral bandpass shapes which do not cancel in the computation of the final spectrum, which leaves a residual standing wave in the overlapped spectrum. We have nearly eliminated this standing wave by using two techniques:

Focus Modulation: Focus modulation is a technique whereby the axial focus is modulated by $+\frac{1}{8}\lambda$ and $-\frac{1}{8}\lambda$ during alternate integrations (usually 30 seconds long). When these alternate scans are averaged, the individual standing waves will be 90° out of phase, thus their amplitudes will cancel.

Beam Peak Scattering: The primary component of the standing wave comes from the reflective path between the receiver feed and the center of the subreflector. By placing an angled reflector (the "Cone of Silence") at the center of the subreflector, power incident at the center of the subreflector will be scattered onto the surface of the primary and scattered onto cold sky, nearly eliminating the main component of reflected power between the subreflector and receiver feed.

If the lines are narrow and the frequency shift is small (say $< \pm 40$ MHz), good results can often be obtained. One must also be careful when frequency switching in regions (spatial or spectral) which may contain multiple spectral lines. Note that one common contaminant in a frequency switched observation is mesospheric CO. The CO $J = 1 \rightarrow 0$ emission from the mesosphere is rather weak, but CO $J = 2 \rightarrow 1$ emission is quite strong (see Figure 5.5).

Frequency switching is effected by switching the phase lock loop offset frequency (the Lock IF) between two nearby settings, usually generated by separate oscillators. The oscillator settings must be set manually. The frequency of switching is usually 5 Hz and is generated by the spectral line multiplexer when so instructed by the computer. The phase lock circuitry must be able to lock at both the signal and reference frequencies. This places a practical limit on the magnitude of the shift of typically $< \pm 40$ MHz. Some receiver systems use the fundamental frequency of the Gunn oscillator as the LO frequency. For these systems, a shift in the loop offset frequency will produce exactly the same shift in the spectrum. Other receiver systems, particularly the high frequency receivers, use a harmonic multiple of the oscillator source as the LO frequency. The desired frequency shift must be divided by the appropriate multiple before setting the loop offset frequencies.

You will usually want to know whether the reference frequency is higher or lower than the signal frequency, or in other words, where the apparent "absorption" and "emission" features appear in the band. This is dependent upon which sideband (upper or lower) is being used. For upper sideband operation, the signal frequency will be higher than the reference frequency, so that the emission line will appear to the right of the reference signal in spectra. The reverse is true for lower sideband operation.

When performing frequency switched observations, you must decide upon the following parameters and give them to the operator:

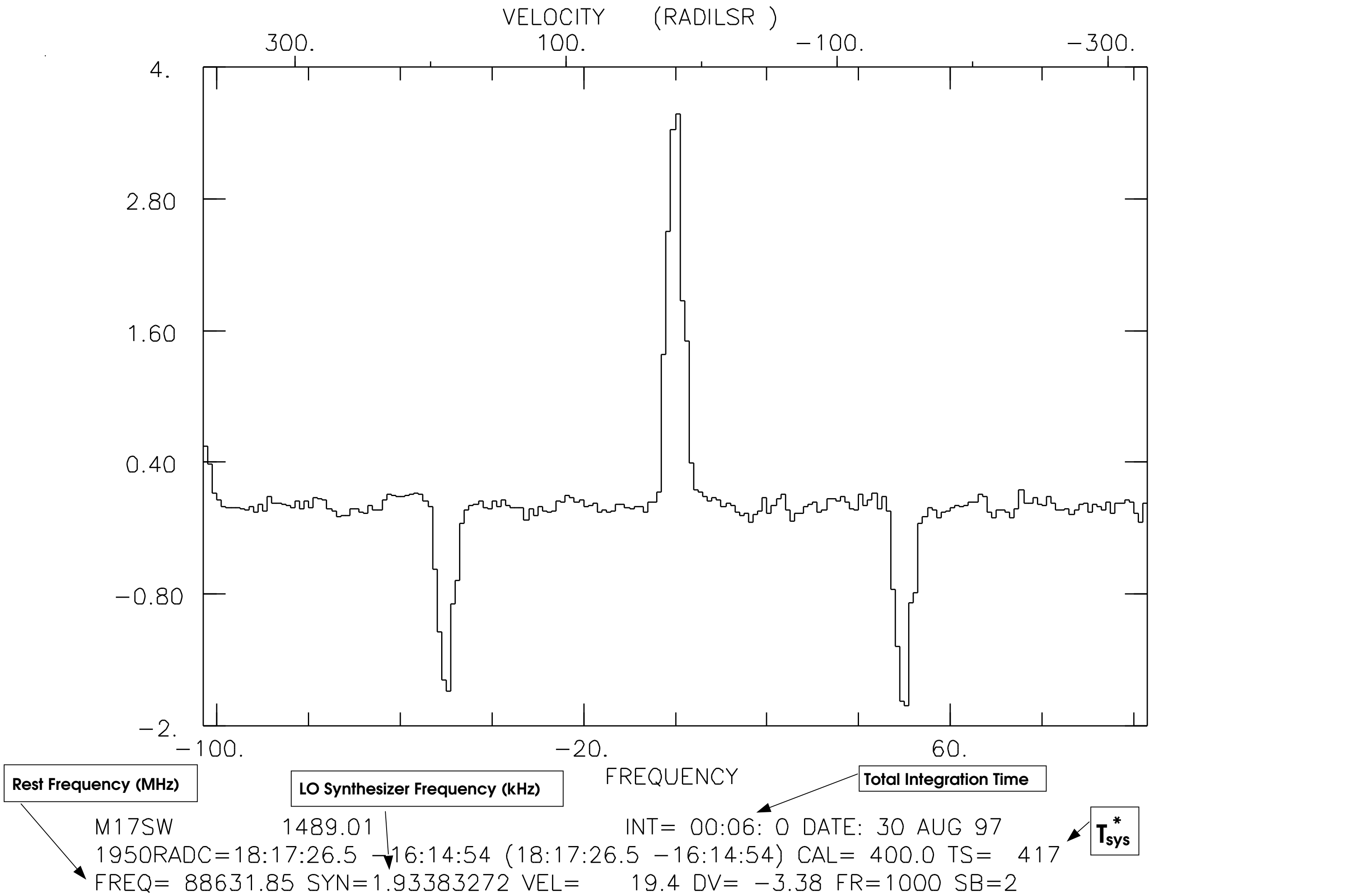

Figure 5.4: Frequency switched spectral line scan analyzed in the unipops program. The frequency switch throw for these measurements was ±25 MHz.

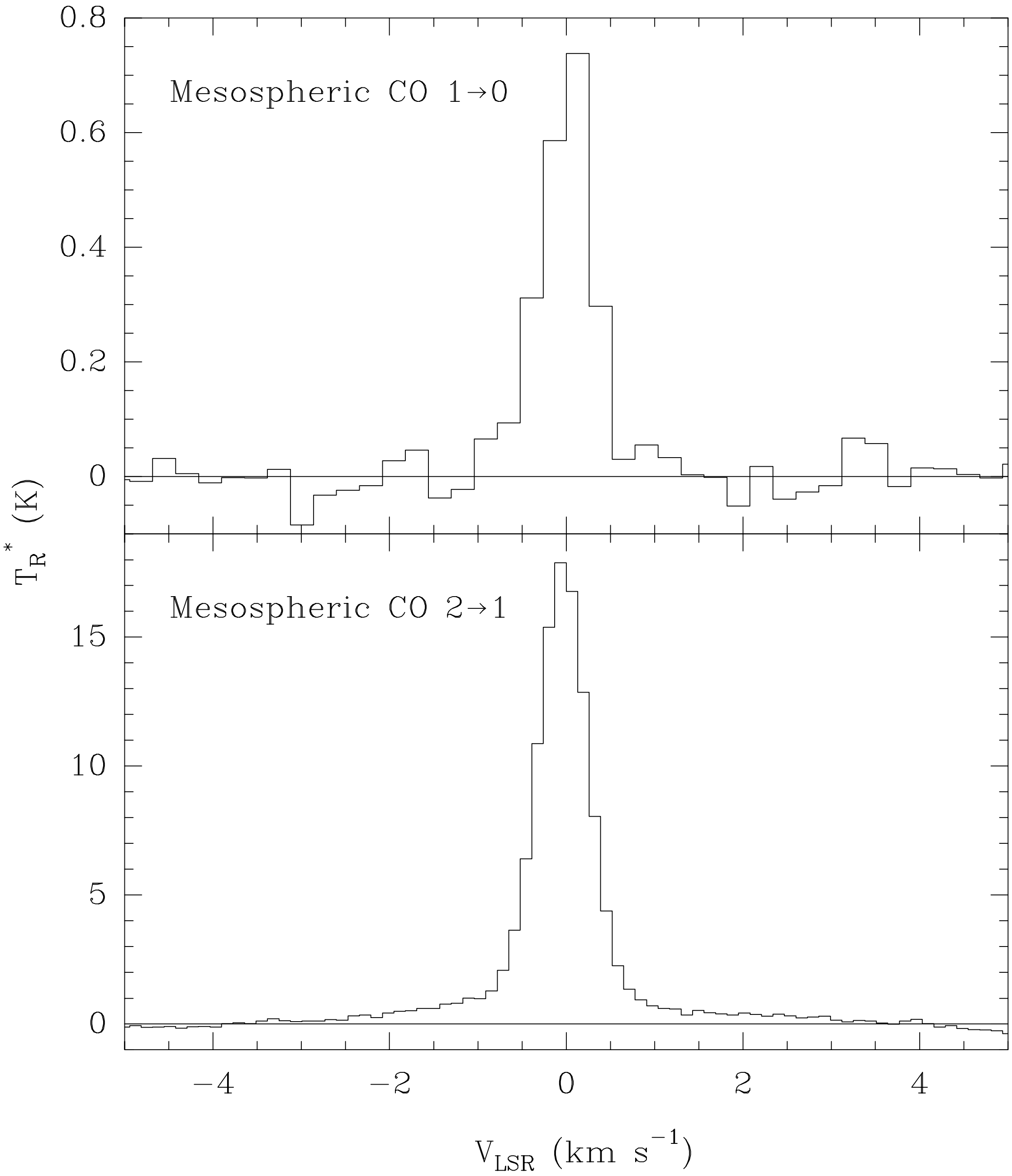

Figure 5.5: Frequency switched spectral line scans of the telluric CO J = 1 → 0 and J = 2 → 1 emission from the Earth's atmosphere.

1. The magnitude, sense, and symmetry of the frequency shift ($< \pm$ 5 MHz);
2. The switch rate (the usual setting is 5 Hz);
3. The total integration time of the scan. Note that the time overhead for frequency switching is about 7%.

To reduce "in-band" frequency switched data in the *line* data reduction system, use the `fold` command.

5.4.5 Beam Switching

Spectral line beam switching can be useful when observing small angular diameter sources and when the best possible baselines are needed. This observing mode involves the nutation (chopping) of the subreflector and a positional movement of the telescope and is thus called the BSP (beam switching plus position switching) mode. The technique is much the same as that used for continuum ON/OFF's (see §6.4.1.1 and Figure 6.2). With the subreflector nutating at a rate of typically 1.25 Hz, the telescope is moved to place the source first in one of the beam positions and then in the other. The beam position which, for a positive source signal, produces a positive response in the spectrometer is called the "positive beam" and a sample taken in this position is called an "ON". Conversely, the beam position which produces a negative response in the spectrometer is called the "negative beam" and a sample taken there is an "OFF". A BSP scan always consists of four samples taken in the order OFF–ON–ON–OFF. The samples are taken in this order to get the best atmospheric rejection, the best baselines, and to reduce telescope movement. The integration time of one of the individual ON or OFF samples controls the total integration time of the scan (sample length times 4).

The beam switching mode usually produces very good spectral baselines. The subreflector switch rate is such that atmospheric changes and filter bank anomalies are most often subtracted out. The primary restriction for beam switching is that the source angular diameter must be smaller than the subreflector throw. The subreflector throw can be varied between 0 and $\pm 4.5'$, but beam throws larger than ± 3 arcminutes are inefficient. The default switching rate is 1.25 Hz. Switch rates of 2.5 and 5.0 Hz are also available. The observing efficiencies are poorer at the faster rates but the cancellation of atmospheric drifts may be better.

You must decide upon the following parameters in a beam switched observation and give them to the operator:

1. The subreflector throw. Changes in the throw must be made manually; the computer must be updated (manually) as to the new value of the throw.
2. The switch rate of the subreflector.
3. The integration time per sample (ON or OFF). The total length of the scan is the sample time x 4.
4. The vane calibration method is available, although it is applied in a different manner than for position switched data (see §5.6).

5.4.6 Mapping

The 12m system offers three modes of spectral line mapping: mapping by manual offsets, automatic mapping of rectangular grids or catalogs in either the total power (TPM), position-switched (PSM or APM), or frequency-switched (FSM) modes, and On-The-Fly mapping. Mapping with manual offsets or rectangular grids is appropriate for small maps or maps with unevenly spaced points. For most rectangular grid mapping, we recommend the automatic position-switched total power mode. With the total power mode, you can choose to observe several ONs per OFF and thereby increase your observing efficiency. On-the-fly mapping is discussed in the separate manual *On The Fly Observing at the 12m*. In the following we describe each of the mapping modes.

5.4.6.1 Manual Offsets

Often an observer will want to make a simple source map consisting of only a few points. In such cases, manual offsets (in RA, DEC) from the center position are the easiest way to proceed. Follow these steps:

1. Enter the center position into a source catalog or tell the operator the name and position so that he can enter it manually;
2. Compute the offsets in angular units. For declination offsets, this is unambiguous. For right ascension, two cases exist:
   (a) You want true angular offsets in the RA direction, *i.e.* with the $\cos(DEC)$ correction made. Tell the operator the magnitude of the offset in minutes and seconds of arc and whether you want to go East (+RA) or West (-RA). Tell him that these are *true angular offsets*;
   (b) You want an RA offset in units of time. Tell the operator the magnitude of the offset in units of minutes and seconds of time and whether to go East or West. Tell him that these are *offsets in time* (*i.e.* **no** $\cos(DEC)$ correction applied).
3. After each integration, loop to Step 2 and select a new point in the map.

The header information on the spectrum displayed by the *line* data reduction program will show any offsets that have been entered. The offsets are given in (real) angular units.

5.4.6.2 Grid Mapping

In the grid mapping modes, you can define a rectangular (RA,DEC) or (lII,bII) grid with different grid spacings in the horizontal and vertical coordinates. You can also define a grid to be acquired at an arbitrary rotation angle. The number of rows and columns must be an odd number. In the total power (TPM) and position-switched modes, you can choose between absolute (Absolute Position Mapping, or APM) and relative reference position (Position Switched Mapping, or PSM) measurements, you can choose to observe several map positions (ONs) for each reference (OFF) position, and you can observe several

OFFs for each vane calibration scan. Frequency switched mapping (FSM) requires no OFF position measurement.

Grid maps can be observed in three different ways: standard grid, which measures all positions on the grid sequentially, spiral grid, which measures all positions on the grid with a spiral pattern, and cross grid, which measures only the points which lie on the central row and column of the grid. Figure 5.6 shows the observing sequence for each variety of grid map.

After defining the grid, you can choose to map a subset by specifying the beginning and ending row numbers, and the beginning and ending column numbers. To use any of the spectral line grid mapping modes, give the operator the following information:

1. The catalog and name of the source (map center position).
2. Standard setup parameters, including the (AZ, EL) pointing offsets, the pointing tolerance, and the focus setting.
3. The reference position offset (relative to the map center) in either the (AZ,EL), (RA,DEC), or (lII,bII) frames if you are doing total power of position-switched mapping.
4. The frequency switch offsets in MHz if you are doing frequency-switched mapping.
5. The horizontal coordinate grid spacing in seconds of arc (real angle).
6. The vertical coordinate grid spacing in seconds of arc.
7. The number of rows in the map. Must be an odd number.
8. The number of columns in the map. Must be an odd number.
9. The beginning and ending rows of the map. (optional)
10. The beginning and ending columns of the map. (optional)
11. The grid rotation angle. (optional)
12. For position- or frequency-switched maps, you must also specify:
    (a) The scan time in seconds.
    (b) The number of ON-OFF pairs per point.
    (c) The number of scans per calibration measurement.
    (d) The number of scans per center position measurement.
13. For total power mapping, you must also specify:
    (a) The integration time per ON and OFF in seconds.
    (b) The number of map positions (ONs) to be observed for each reference position (OFF).

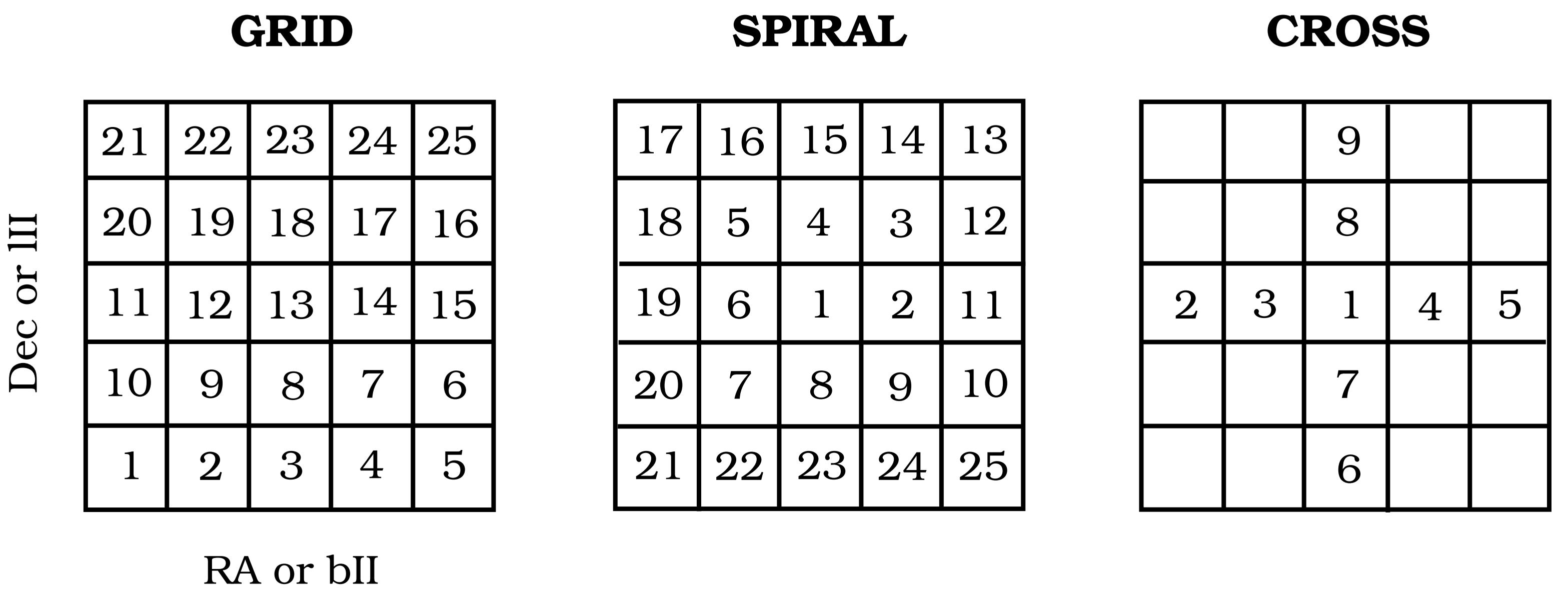

Figure 5.6: Grid map observing sequence for all 12m grid mapping modes.

(c) The number of OFFs for each vane CALIBRATE.

Display of position- and frequency-switched map measurements is the same as that used to display regular PS or FS measurements. The spectrum of a single total power map point is displayed in *line* using the ton procedure:

```
Line> install ton
Line> scan# ton
```

where scan# is that of the ON position.

To display a contour map of peak or integrated intensity versus position, it is best to use the CLASS program. See §2.4.1 for information on how to port your 12m data to CLASS format. Manuals for the CLASS program are also available.

5.4.6.3 When Should I OTF Instead of Grid Map?

As a general rule-of-thumb, it is best to use OTF mapping instead of the step-and-integrate mapping described in this section when your map field is larger than about $6'$ in either RA or DEC and your target spectral line is expected to be reasonably strong. For those rare cases when OTF is not suitable, one must decide which step-and-integrate mapping technique to use. There is no hard rule to determine whether one should use PSM or TPM, the total power mapping mode. TPM is more efficient in the sense that you can use one OFF scan with several ONs. However, PSM may produce better baselines because of the switching pattern. As a general recommendation, we suggest that you use TPM for maps of strong lines and large mapping grids; use PSM if the lines are weak and baseline stability is critical. APM is also an alternative to PSM: it uses the same OFF–ON–ON–OFF... pattern but the mapping positions are taken from discrete catalog entries rather than a grid built from offsets from a single central position. FSM is another alternative for those cases where frequency switching can be used (see §5.4.4).

5.4.6.4 An Important Note About Spatial Sampling

The following is due to Darrel Emerson

When setting up your map observations, it is important to keep in mind the following facts about sampling and aliasing in radio astronomical mapping data. If you want to represent the full resolution of the telescope, you have to sample the data often enough to represent all the spatial frequencies detected by the dish. You can think of the extreme edges of the dish of diameter D as part of an interferometer of spacing D, which has to be sampled at $\frac{\lambda}{2D}$. Depending on the illumination taper, this corresponds typically to sampling at about 2.4 or 2.5 points per FWHM. Of course, if there is zero, or by some definition "negligible", illumination at the edge of the dish, you won't be sensitive to such high spatial frequencies. It will be just the same as a smaller dish of diameter d equal to the diameter of that part of the dish that has significant illumination, and the sampling will be calculated from $\frac{\lambda}{2X}$, where X is defined as the diameter of the illuminated part of the surface.

It's useful to consider what happens if you undersample data. Assume that the undersampling happens on the sky, rather than in later in the data processing. Suppose you have a 10m dish, but you only sample at $\frac{\lambda}{2\times 8m}$ rather than the $\frac{\lambda}{2\times 10m}$ that you should. That means that the spatial frequencies present from the dish baselines of 8m to 10m get reflected back into the spatial frequencies of 8m down to 6m. Not only have spatial frequencies from the 8m to 10m baselines been lost, but valid spatial frequencies from baselines of 6m to 8m have been corrupted. You can't tell if structure in your map with a spatial wavelength of $\frac{\lambda}{7m}$ is genuine, or was really structure at $\frac{\lambda}{9m}$ which has been aliased on top of any genuine $\frac{\lambda}{7m}$ spatial wavelength signal. In this sense, undersampling the sky is really twice as bad as you might have thought.

How important this undersampling is depends on exactly what the illumination taper is, how important it is that you retain the maximum possible resolution of the telescope, how good a dynamic range you want in the observations, and at some level how much fine scale structure there is in the source itself. If you only sample at 0.8 Nyquist (*e.g.* $\frac{FWHM}{2}$ rather than $\frac{FWHM}{2.5}$), what matters is the energy in the data at spatial wavelengths shorter than $\frac{\lambda}{2\times 0.8\times D}$. So in a sense you need to ask what the illumination taper is at a radius of $0.4 \times D$ on the dish surface. The spatial frequency response of a single dish is the autocorrelation function of the voltage illumination pattern. So, you need to calculate how much area there is under the 2-D autocorrelation function beyond spatial frequencies of $0.8 \times D$, compared to the area within $0.8 \times D$. This ratio is some measure of the dynamic range. A better definition of dynamic range might take into account the spatial frequency structure of the source. If the source has no structure on scales smaller than $\frac{\lambda}{2\times 0.8\times D}$, then you don't need to sample at the full $\frac{\lambda}{2\times D}$ anyway.

This is one circumstance where it is perfectly rigorous to undersample the data. If, say, you have a 10m dish, and you are taking data to compare with other observations using a 1m dish at the same wavelength (or the equivalent number of wavelengths at some other frequency) then you only need to sample the data at $\frac{\lambda}{2\times 5.5m}$ or $\frac{\lambda}{11m}$. This is so because, when sampling a 10m dish as if it were a 5.5m dish, the spatial frequency components from baselines of 5.5m out to 10m will be reflected back into the data as if corresponding to baselines of 5.5m down to 1m. So, the spatial frequency terms of 1m baseline and below will not have been corrupted. The data analysis of this undersampled data would apply a spatial frequency cutoff at 1m, and there will have been no corruption in this smoothed data caused by the undersampling. Putting it in more general terms, if you are going to be smoothing a dish of diameter D to simulate observations made with a smaller dish of diameter d, then the sampling interval only needs to be $\frac{\lambda}{d+D}$ rather than $\frac{\lambda}{2\times D}$.

There are other aspects that make it desirable to sample **more** often than the Nyquist rate, as we recommend for OTF observing. These are practical points like how well gridding or interpolation works with a finite sized gridding or interpolation function. A little oversampling may enable you to reduce the convolution (interpolation) function by a factor of a few, saving a huge amount of computational overhead at the expense of a few per cent more data.

5.5 Spectral Line Sensitivities

The spectral line calibration technique generally used at the 12m is the chopper wheel or vane method. The effective system temperature given by this technique includes corrections for atmospheric attenuation and antenna spillover, blockage, and ohmic losses. The method does not include a correction for error pattern losses as the error beam will couple differently to different sources. The effective system temperature, T^*_{sys} , on the scale defined above, is given by

$$T^*_{sys} = \frac{\left(1 + \frac{G_i}{G_s}\right)[T_{rx} + T_A(sky)]}{\eta_l \eta_{fss} \exp(-\tau_0 A)} \tag{5.5}$$

where

G_i is the image sideband gain;

G_s is the signal sideband gain;

T_{rx} is the receiver DSB noise temperature;

$T_A(sky)$ is the temperature of the sky (definition given below);

η_l is the rear spillover, blockage, scattering, and ohmic efficiency;

η_{fss} is the forward spillover efficiency;

τ_0 is the atmospheric optical depth at 1 airmass (the zenith); and,

A is the number of airmasses, generally given by 1/sin(elevation).

$T_A(sky)$ is given by the equation

$$\begin{aligned} T_A(sky) &= T_{sky} + T_{ant} + T_{cmbr} \\ &= \eta_l T_m [1 - \exp(-\tau_0 A)] + (1 - \eta_l) T_{spill} + \eta_l T_{bg} \exp(-\tau_0 A) \end{aligned} \tag{5.6}$$

where

T_m is the mean atmospheric temperature,

T_{spill} is the spillover temperature, and

T_{bg} is the cosmic background temperature.

Note that T_m, T_{spill}, and T_{bg} are actually equivalent Rayleigh-Jeans temperatures of the point on the Planck blackbody curve corresponding to the same frequency. This correction factor is given by Equation 6.10. For simplicity, we will retain the symbol "T" for temperatures, but in calculations "T" should be replaced by "J(ν,T)".

The rms noise level for a given integration time, assuming equal integration time at the ON source and OFF source reference positions, is given by the radiometer equation (see Appendix F for a general derivation of the radiometer equation for non-equal ON and OFF source integration times)

$$T_{rms} = \frac{2T^*_{sys}}{\eta_{spec}\sqrt{\Delta\nu t_{scan}}} \tag{5.7}$$

where

$\Delta\nu$ is the bandwidth of an individual channel in the spectrometer (in Hz),

η_{spec} is the efficiency associated with the spectrometer used. $\eta_{spec} = 0.81$ for the Millimeter Autocorrelator (MAC) and 1.0 for the filter banks. See Appendix D for more information.

t_{scan} is the total integration time, including ON and OFF source time (in seconds).

Note that for observations of unpolarized signals with receivers that have two polarization channels, the two channels can be averaged to reduce the effective system temperature. In this case, T^*_{sys} is the average of the effective system temperatures for the two polarization channels.

5.6 Calibration

5.6.1 Vane Calibration

The calibration mode used for almost all spectral line observations at the 12m is the vane or chopper wheel method. In this method, a calibration signal is generated by differencing the signals recorded first on cold sky and then on an ambient temperature absorber. In 12m vernacular, a vane is a paddle covered with microwave absorber that is switched in and out of the beam at a rate of about 1 Hz. A chopper wheel is, in this case, a chopping blade whose solid portions are covered with absorber and which rotates at a rate of typically 10 - 50 Hz. The calibration technique is identical with the two devices. The receivers currently in use at the 12m all use a common central vane.

Chopper wheel calibration has been discussed extensively in the literature (see Ulich & Haas, 1976, ApJS, 30, 247, and Kutner & Ulich, 1981, ApJ, 250, 341). The technique corrects for atmospheric attenuation and several telescope losses. At the 12m, the temperatures resulting from this technique are on the T^*_R scale (Kutner & Ulich) which means that the temperatures are corrected for the atmosphere and all telescope losses except for coupling of the source and beam. The beam is defined here to include the central diffraction lobe, all near-in sidelobes, and the error pattern (error pattern losses are often the largest of the uncorrected losses). Observers should be aware that other observatories using the chopper wheel method have different definitions of the basic temperature scale. Exercise care when comparing data!

An essential part of the chopper wheel calibration method is the specification of the calibration scale temperature T_C, which is given by

$$T_C = \frac{T_{hot} - T_A(sky)}{\eta_l \eta_{fss} \exp(-\tau_0 A)} \tag{5.8}$$

where $T_A(sky)$ is given by Equation 6.9. For observations under typical atmospheric conditions, $T_C = 400$ for single sideband operation and 800 for double sideband operation. Note that T_C varies with elevation, particularly for double sideband observations on the wings of an atmospheric line such as at 115 GHz.

The procedure for performing a vane CALIBRATE is the following:

1. Set the calibration scale temperature T_C. As explained above, T_C is approximately 400 for SSB receivers and 800 for DSB receivers. The precise value of T_C is dependent upon efficiency factors, temperature, atmospheric optical depth and elevation or airmass.

2. Perform a calibration cycle (called a CALIBRATE) at intervals which you prescribe. The interval should be small enough that the atmospheric transmission during the interval does not change appreciably. This depends on the atmospheric optical depth and its stability and the elevation. During stable conditions of low optical depth, a CALIBRATE every 10-15 minutes is usually sufficient. If the atmosphere is choppy or the elevation is changing rapidly as when the source is rising or setting, more frequent CALIBRATEs may be necessary. The operator can command the system to perform a CALIBRATE before each position switched scan or before a specified block of scans. The length and number of repeats of a given CALIBRATE can also be specified. The default is 30 seconds, with the vane and sky sampled 15 times each at 1 second per sample.

3. The result of a CALIBRATE is loaded into the gains array. To examine the gains, type `g1` for receiver channel 1 and `g2` for channel 2. Exact definitions of the signal processing are given in Section §5.7.

4. During position and frequency switched observations, the telescope moves to the OFF position to take the CALIBRATE.

5.6.2 Direct Calibration

Note: The staff does not recommend this calibration procedure. We describe it here for completeness.

In the direct calibration mode, the data are scaled by the system temperature and the atmospheric attenuation according to the relation

$$T_A = \frac{\mathsf{SIG} - \mathsf{REF}}{\mathsf{REF}} \times T_{sys} \times \exp(A\tau_0), \tag{5.9}$$

where SIG is the signal array, REF the reference array, T_{sys} the system temperature, τ_0 the zenith optical depth, and A the airmass. The exact expressions for no-cal signal processing are discussed below. The observer is responsible for the computation of T_{sys} and the measurement of τ_0. The value for T_{sys} can include efficiency factors, or the antenna temperature can be scaled up in the data reduction and post-processing stage. One reasonable definition of T_{sys} is

$$T_{sys} = \frac{\left(1 + \frac{G_i}{G_s}\right)(T_{rx} + T_{sky})}{\eta_l \eta_{fss}} \tag{5.10}$$

where G_i and G_s are the image and signal sideband gains, T_{rx} is the receiver noise temperature, T_{sky} is the antenna temperature of the sky (Equation 6.9), η_l is the rear spillover efficiency, and η_{fss} is the forward spillover efficiency. With this definition, the resulting antenna temperature is on the same scale (T_R^*) as with the chopper wheel calibration.

This calibration scheme has a certain appeal because it is direct and easy to understand. However, the method has several difficulties which prevent it, in general, from being as accurate as the chopper wheel method. First, in the absence of an automatic HOT/COLD/SKY load system (which the 12m doesn't have), you must make several time-consuming observations. These include tipping scans to measure the atmospheric optical depth, and manual HOT/COLD loads to measure the receiver noise temperature and possibly the sky temperature. If these measurements are not made frequently, receiver and atmospheric drifts may introduce calibration errors. In addition, measurement of an average atmospheric optical depth may not adequately correct for local cloudlets and other atmospheric anomalies. Finally, the chopper wheel method depends only weakly on η_l, whereas the direct calibration method depends strongly on it.

Although we do not recommend the no-cal method for most cases, you should follow this procedure if you choose to use it.

1. Perform an ordinary VANE cal to look for bad channels and give the operator a list of the bad channels;

2. Tell the operator you will be using the no-cal method. He will first perform a dummy CALIBRATE to zero the bad channels. You will not need to perform any more calibrates.

3. Tell the operator the value of T_{sys} you wish to use. It's up to you to decide how to calculate this number, but you will probably want to measure the receiver noise temperature by a HOT/COLD load, in the least.

4. Perform a tipping scan (see §6.5.1).

5. Repeat steps (3) and (4) at intervals short enough to catch any significant system or atmospheric changes.

5.7 Signal Processing

5.7.1 Position and Frequency Switched Data

5.7.1.1 Vane/Chopper Calibrates

When a vane calibration is performed, a calibration array called the gains array is computed according to the formula

$$C_i = \frac{R_{ci} - Z_i}{S_{ci} - R_{ci}} \times T_C, \tag{5.11}$$

where

C_i is the effective system temperature for channel i,

S_{ci} is the calibration signal (vane over the feed) for channel i,

R_{ci} is the calibration reference (cold sky) for channel i,

Z_i is the zero value response of channel i with no input signal, and

T_C is the calibration scale temperature.

The array of C_i elements is called the gains array. The average effective system temperature of all channels in the multiplexer,

$$T_{sys} = < C_i >, \tag{5.12}$$

is displayed and updated on the on-line status monitor each time a CALIBRATE is performed. Note that T_{sys} is an average of both receiver channels when a two-channel receiver is in use.

The calibrated antenna temperatures (T_R^*) that are recorded on disk are calculated by the formula

$$(T_R^*)_i = \frac{S_i - R_i}{R_i - Z_i} \times C_i, \tag{5.13}$$

where

$(T_R^*)_i$ is the calibrated antenna temperature for channel i,

S_i is the Source or ON signal, and

R_i is the Reference or OFF signal.

5.7.1.2 No-Cal Signal Processing

In the no-cal mode, the antenna temperatures are calculated from the relation

$$(T_A)_i = \frac{S_i - R_i}{R_i - Z_i} \times T_{sys} \times \exp(A\tau_0), \tag{5.14}$$

where τ_0 is the zenith optical depth (called TAU0 in the control system), and A is the airmass, calculated as $1/\sin(elevation)$. All other symbols are defined in §5.7.1.1.

5.7.2 Beam Switched Data

Beam switched data are calibrated using the vane but the signal processing is different from position and frequency switching. When a calibrate is performed during a beam switching session, the gains array is defined as

$$C_i = \frac{1}{S_{ci} - R_{ci}} \times T_C, \tag{5.15}$$

where the terms are defined above. The antenna temperature scale is given by

$$(T_R^*)_i = (S_i - R_i) \times C_i. \tag{5.16}$$

5.8 Changing the Intermediate Frequency

Occasionally an observing situation may arise in which a change in the Intermediate Frequency from the nominal 1.5 GHz is either necessary or desirable. One example of this is when the program line is just outside the tuning range of the local oscillator. Another example occurs when, for double sideband observations, it is advantageous to observe lines from both the signal and image sidebands for pointing, calibration, or simultaneous line search purposes and the image line is just outside the normal spectral bandpass.

These observing situations can be accommodated provided the IF needs to be changed by only a small amount. The IF system has a bandpass filter centered at 1500 MHz with a bandwidth of ±300 MHz. Any change of the IF must thus fit within the 600 MHz IF bandwidth, leaving room to include the filter bank bandwidth. Hence, the minimum IF can be 1200 MHz plus $\frac{1}{2}$ the filter bank bandwidth and the maximum IF can be 1800 MHz less $\frac{1}{2}$ the filter bank bandwidth. Lines in opposite sidebands can be separated by at most 3600 MHz less $\frac{1}{2}$ the filter bank bandwidth, or in the least by 2400 MHz plus $\frac{1}{2}$ the filter bank bandwidth.

To adjust the IF bandwidth, the first IF synthesizer, which is normally set to 109.50000 MHz, must be changed. The equation for determining the synthesizer frequency is

$$f_{syn} = \frac{f_{IF} + 2442\ MHz}{36}, \tag{5.17}$$

where f_{IF} is the desired IF. If the lines are in opposite sidebands,

$$f_{IF} = \frac{(f_u - f_l)}{2}, \tag{5.18}$$

where f_u is the upper sideband center frequency and f_l is the lower sideband center frequency. This intermediate frequency must be entered into the control computer so that the local oscillator synthesizer frequency will be correctly calculated.

Note that if the two target lines are at the center of their respective sidebands, they will fall on top of each other in the resultant spectrum. To keep this from happening, offset the line rest frequencies from the band center. If the signal sideband center frequency is offset by an amount δ, the signal and image sideband lines will be separated by 2δ and will be symmetrically displaced about the center of the final spectrum.

To observe with a non-standard IF, follow this procedure:

1. Discuss your intentions with a staff member well in advance of the observations;
2. Calculate the new synthesizer frequency according to the equations above. Make sure that you are not exceeding the 600 MHz bandwidth of the IF system.
3. Ask the operator to dial the synthesizer frequency into the IF synthesizer that is nominally set to 109.5 MHz.
4. Ask the operator to set the new IF into the control computer.
5. If appropriate, offset the signal band center frequency from the line rest frequency to prevent overlap of signal and image lines.

6. Remember to have the synthesizer set back to 109.50000 MHz when the special observations are finished.

Step (6) above is especially important to remember as the computer does not check the IF synthesizer for a correct setting. If you (or the next observer) resume standard observations and the synthesizer is not reset to 109.5 MHz, the band center will be offset from what you intend. In addition, we highly recommend that you check your special observing configuration on a strong test line before conducting program observations on weak lines.

5.9 Spectral Line Status Monitor

The spectral line status monitor provides basic information about the status of the telescope and the observations that are underway. The observer should check the monitor frequently to see that the telescope and control system are configured as they should be. Figure 5.7 shows a sample monitor screen divided into several boxes. Each numbered box indicates a section of the display which describes a particular set of attributes of a spectral line measurement. Only box 7 differs from the continuum status display (see §6.7:

Box 1: Scan number, source name, and timing information.

- **SCAN:** Current scan number.
- **SOURCE:** Source name.
- **HORIZON:** Time to 15° elevation (rise or set).
- **LST:** Current local sidereal time.
- **UTC:** Current coordinated universal time.
- **DUT1:** UT1-UTC time correction.
- **date:** Current year (top) and date (bottom).
- **OBS:** Current observer initials (top) and data file number (bottom).
- **OPR:** Current operator initials.

Box 2: RA/Dec and lII/bII position information.

- **TOTAL:** Current total (apparent plus offsets) RA and Dec.
- **B1950.0:** Current Equinox B1950 RA and Dec.
- **APPARENT:** Current apparent RA and Dec.
- **GALACTIC:** Current lII and bII.
- **OFFSET:** Current applied RA and Dec offsets.

Box 3: Apex position information.

- **NS:** North (top) and south (bottom) focus translation stage offset position in millimeters.

EW: East (top) and west (bottom) focus translation stage offset position in millimeters.

Box 4: Azimuth and elevation position and pointing offset information.

COMMAND: Commanded azimuth and elevation (spherical coordinate conversion plus pointing corrections).

ACTUAL: Actual azimuth and elevation encoder readings.

ERROR: Difference between COMMAND and ACTUAL azimuth and elevation.

OFFSET: Total azimuth and elevation offsets (sum of pointing offsets plus subreflector beam throw).

POINT: Azimuth and elevation pointing model corrections.

PSREF: Reference position offset in azimuth and elevation.

Box 5: Receiver calibration and tipper information.

ATM: Number of air masses toward current elevation.

RCVR: Receiver name.

RBAY: Receiver bay.

F0: Axial focus zero position in millimeters.

TC: Calibration scale factor for receiver channels 1 (top) and 2 (bottom).

TAU0: Actual (top) and 225 GHz (bottom, measured continuously using a tipping radiometer) zenith opacity.

FWHM: Beam FWHM (top) and HWHM (bottom, used for five-point measurements) in mm:ss.

TSYS: Channel 1 (top) and 2 (bottom) system temperatures in K.

MM_H2O: Millimeters of water vapor at zenith based on the 225 GHz tipping radiometer measurement of τ_0 and a conversion of 1 millimeter H_2O equals an opacity of 0.05 at 225 GHz.

Box 6: Subreflector beam and quadrant detector position information.

+BEAM: Azimuth and elevation position for the +Beam in mm:ss.

-BEAM: Azimith and elevation position for the −Beam in mm:ss.

QX: Quadrant detector x-axis position in millimeters.

QY: Quadrant detector y-axis position in millimeters.

Box 7: Frequency, velocity, and calibration information.

LINE: Spectral line name for current transition frequency.

BW: First (top) and second (bottom) filter bank spectrometer channel width in kHz.

CHANNEL: The multiplexer channels used for the first (top) and second (bottom) filter bank.

CONF: A code indicating the whether the filter banks for configured for serial (SER) or parallel (PAR) operation.

MAC_BW: Millimeter Autocorrelator (MAC) bandwidth in MHz.

OBJ_V: Source velocity in chosen reference frame in km/s.

ANT_V: Antenna velocity in chosen reference frame in km/s.

FRAME: Velocity frame of reference code.

TYPE: Velocity type.

SB: Signal sideband (upper or lower) for channel 1 (top) and channel 2 (bottom).

LO: Local oscillator multiplication factor.

IF'S: Intermediate frequencies in MHz.

FREQUENCY: Rest frequencies for channels 1 (line 1) and 2 (line 2), in GHz, with their associated LO synthesizer frequencies (lines 3 and 4, respectively), in MHz.

CAL: Calibration type.

FB_OFF: Filter bank offset in MHz.

MAC_OFF: Millimeter Autocorrelator (MAC) offset in MHz.

SPEC_RUN: Indicates that this is a spectroscopy measurement with the filter banks.

MAC_RUN: Indicates that this is a spectroscopy measurement with the Millimeter Autocorrelator (MAC).

BAD_CHAN: Filter bank channels flagged by the on-line system.

Box 8: Telescope tracking and weather information.

TOL: Input and actual tracking tolerance in m:ss.

FOCUS: Input and actual axial focus at the current elevation in millimeters.

TORR: Barometric pressure in Torr.

%RH: Relative humidity.

T_AMB: Ambient temperature in C.

REFRT: Input and actual refraction constant for elevation refraction pointing correction in arcseconds.

Box 9: Current observation scan and integration time information.

MODE: Observing mode.

SCANS: Number of scans requested.

SAMPLES: Number of continuum on/off samples requested.

SEC: Total (top) and remaining (bottom) sample time in seconds.

TIME: Total (top) and remaining (bottom) integration time for this scan in mm:ss.

```
1
SCAN     SOURCE    HORIZON      LST        UTC              DUT1     1996   OBS  OPR
 7707  Mars            6:41    9:05:53  13:20:19         -0.011   08 Nov  sys  VLG
RNAME                                   13:20:19                          289

2
              R.A.          DEC.
TOTAL       10:30:07.8  11:15:28.4
B1950.0      0:00:00.0   0:00:00.0
APPARENT    10:30:07.8  11:15:28.4
GALACTIC     133.94746     1.06432
OFFSET       0:00:00.0   0:00:00.0

3
   APEX
NS +0.500
   +0.500
EW +0.000
   +0.000

4
              AZIMUTH        ELEVATION
COMMAND   132:10:58.2     61:37:20.0
ACTUAL    132:10:58.2     61:37:23.6
ERROR       0:00:00.1    -0:00:03.6
OFFSET      0:00:00.0     0:00:00.0

POINT       0:00:11.5    -0:00:18.1
PSREF       0:00:00.0     0:00:00.0

5
 ATM   RCVR  RBAY  F0    TC    TAU0   FWHM   TSYS
 1.14   1mmhi  4  43.3 400.0  0.223  0:30    764
MM_H2O-> 2.24          400.0  0.112  0:15    735

6
+BEAM   1:00  0:00   QX -6.30
-BEAM  -1:00  0:00   QY +3.19

7
                                                          LINE->          HCN
    BW  CHANNEL CONF  HS_BW   OBJ_V ANT_V FRAME TYPE  SB   LO IF'S    FREQUENCY
F1 1000   1 256 SER   600.0   -14.7  -0.1  GEO   RAD  USB   3  100    265.886432
F2 2000 257 512 SER       2               CAL->VANE  USB    1500    265.886432
FB_OFF->    0.0      HS_OFF->   0.0   0.0     SPEC_RUN   HS_RUN      1956.293040
BAD_CHAN->                                                           1956.293040

8
           TOL  FOCUS  TORR  %RH  T_AMB  REFRT
INPUT     0:05  45.7   613     3   13.6  46.2
ACTUAL    0:04  45.7   WIND-> 113 @ 18   46.2

9
MODE SCANS  SAMPLES   SEC    TIME
BSP     0        4    90.0   6:00
                 2    90.0   3:00
```

Figure 5.7: Spectral line on-line status monitor. The numbered boxes indicate sections of information on the display which are explained in §5.9

Chapter 6

Continuum Observing

6.1 Startup Checklist

Once the scientific goals of the observing program are in mind, you must make the following decisions:

Precise Observing Frequency: When choosing a precise frequency, consider both the absorption spectrum of the atmosphere and the possibility of contamination by galactic spectral line emission.

Observing Mode: Select the appropriate observing mode from those available, and decide upon the setup parameters. Observing modes supported are ON/OFF's, single beam and dual beam on-the-fly and grid mapping, and utility programs such as five-point maps, sky tips, and focus checks.

Beam Throw: A particularly important setup parameter for beam-switched observations is the beam throw. The throw can be varied from 0 to $\pm 4.5'$ (a throw larger than $\pm 3'$ may be inefficient in terms of the blanking necessary).

Observing Time Budget: As with all observations, you should carefully plan the observing program to include time not only for observations of the program sources, but for pointing, focusing, and calibration.

When beginning a continuum observing run, we recommend that you follow these steps:

1. Have the operator tune the receiver to the frequency of your program observations and make any other necessary changes.

2. Perform a HOT/COLD load observation to measure the receiver noise temperature and to set calibration scale factors.

3. Check the telescope pointing and focus on a standard source, preferably in the same part of the sky as your first program source.

4. Make a short ON/OFF observation of a strong standard source such as a planet to see that the telescope and receiver systems are functional, at least in gross terms.

5. Observe a standard source using the system configuration and observing techniques you intend to use for program observations.

6. Commence the program. Remember to check pointing and focus and to observe flux density standards frequently.

We strongly recommend that you invest the time to perform these checks. Remember that *the responsibility for the integrity of the data rests with the observer.*

6.2 Selecting an Observing Frequency

You should take some care in the precise choice of a continuum observing frequency. In addition to the scientific goals that determine the approximate frequency, you should also consider two other factors: what frequency gives the best atmospheric transmission, and will the observations be affected by contamination from spectral lines in the bandpass. In the 3 mm band, maximum transmission occurs near 90 GHz, while in the 1.3 mm band, maximum transmission occurs near 230 GHz. Figure 6.1 is a plot of the atmospheric transmission as a function of frequency for the bands covered by the 12m receivers.

If the observations are near molecular clouds, spectral line contamination can seriously affect continuum measurements. This is particularly true if the continuum bandpass contains strong molecular lines, such as those from CO, HCN, or HCO+, but even a series of weak lines, when integrated over the band, can be a problem. As receiver sensitivities have improved, observers have discovered that some molecular line sources contain what is nearly a continuum of spectral lines – the so-called "spectral line forest". We advise continuum observers to research the sources they wish to observe to find if any of these molecular line sources are either associated with the program source or along the line of sight. You should then consult a molecular line listing such as the F. J. Lovas Catalog (1986, J. Phys. Chem. Ref. Data, 15, 251) to pick the optimum observing frequency. For continuum measurements the 12m receivers operate in the double sideband mode with 600 MHz of bandwidth in each sideband and a sideband separation of 3.0 GHz.

6.3 Observing Basics

You can perform several types of continuum observations at the 12m. The most common types are:

- ON/OFF's – With the subreflector chopping, the telescope moves first to one beam position and then the other. Appropriate for point source observations.
- Grid Mapping – The telescope steps through a rectangular azimuth/elevation grid.
- On-The-Fly Mapping – Beam-switched data are acquired every 0.125 seconds while the telescope is driven continuously over a specified map field.

This section describes the basic considerations, terminology, and techniques for making these observations. Detailed descriptions of the observing procedures are given in Section 6.4

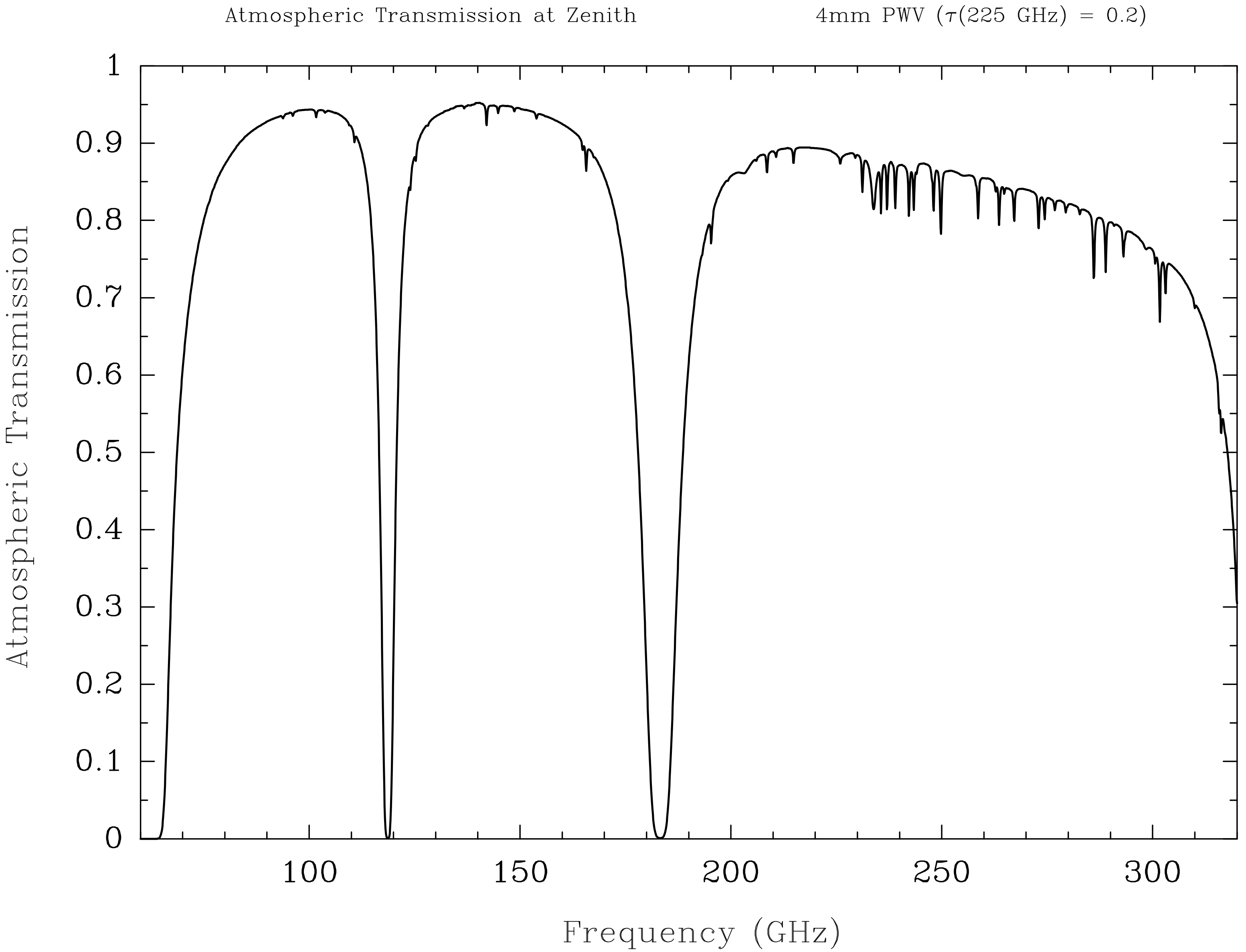

Figure 6.1: Atmospheric transmission as a function of frequency. The range in frequency shown covers that accessible with the 12m receivers. Typical atmospheric conditions with an atmospheric water content of 4mm precipitable water vapor have been used in these calculations.

6.3.1 Switching Modes

In contrast to spectral line signals, continuum signals are fundamentally indistinguishable from other broadband noise sources, such as atmospheric emission, spillover radiation from the ground and surrounding buildings, and receiver gain fluctuations. Such noise sources (particularly atmospheric emission) are, in fact, usually stronger than the celestial signal. Furthermore, atmospheric emission may change over very short time scales ($\ll 1$ second) and may vary significantly at sky positions separated by as little as a few arc minutes.

To distinguish the celestial signal from other broadband signals, the 12m systems provide various switching and subtraction techniques. Most of the techniques employ beam switching of one type or another. Beam switching is accomplished by a nutating subreflector (also known as a chopping secondary). The default subreflector switch rate is 4 Hz. The subreflector throw can be varied from $0'$ to its physical limit of $4.5'$. The two subreflector positions are termed the +BEAM and the −BEAM. With the analog phase-sensitive detectors, the source produces a positive deflection on the chart recorder when it is in the +BEAM and a negative deflection when in the −BEAM.

Two types of beam switching are employed: single beam and dual beam. For point source ON/OFF scans, a dual beam observation means that during the course of the scan, the telescope is positioned so that the source is alternately in the +BEAM and the −BEAM. For mapping observations, the dual beam mode means that source emission is expected in each of the subreflector beam positions and that the dual beam restoration algorithm (Emerson, Klein, & Haslam 1979, A&A, 76, 92) will be applied. A single beam observation, for either point source or mapping observations, means that source is observed in only one of the subreflector beam positions.

The other switching mode is total power position switching for which the subreflector is locked to a single position (the +BEAM, by convention). Observers occasionally use this mode to make accurate aperture efficiency measurements so as to avoid any efficiency losses incurred during subreflector switching. These observations usually use a planet whose strength is large compared to the emission differences of the atmosphere at the two sky positions of a position switched observation. In the rare circumstance in which a source is so extended that the dual beam restoration mapping technique is inapplicable, total power observations may be required. For most standard observing procedures, observers prefer beam switching over total power position switching, as it provides much better cancellation of the atmosphere.

6.3.2 Checking the Subreflector Throw

In the following, we give two methods which can be used to measure the true subreflector beam throw.

Checking the Subreflector Throw with a Continuum Az-El Grid Map or Continuum Raster Scan:

Suppose we are observing at 3mm and have set the subreflector for a nominal $4'$ beam throw ($\pm 2'$). To confirm this, have the operator setup to do either a "Continuum Az-El Grid Map" or a "Continuum Raster Scan" on a bright continuum source, such as a planet. I will describe both methods below:

Continuum Az-El Grid Map:

Ask the operator to setup a Continuum Az-El Grid Map with an integration time per sample of 5 seconds, an azimuth grid spacing of 5 arcseconds, 1 row, 120 columns, scan direction azimuth, and all other parameters set to their default values. This will give you an azimuth scan 10 arcminutes in length which will take approximately 10 minutes to acquire. To process this measurement, you can use the following commands in *condar*. Note that you need to batch the *dbgauss.prc* procedure only once per *condar* session:

```
Condar > batch /home/obs/sys/proc/dbgauss.prc
Condar > bdrop = 0
Condar > edrop = 0
Condar > get scan_number
Condar > switched
Condar > dbgauss
```

The procedure *dbgauss* will do a two-Gaussian fit to your measurement and report the measured beam separation.

Continuum OTF Scan:

Ask the operator to setup for a Continuum OTF Scan with a ramp-up distance of 30 arcseconds, a scan distance of 10 arcminutes, a scan rate of 10 arcseconds/second, 1 row, and all other parameters set to their default values. To process this measurement, you can use the following commands in *condar*:

```
Condar > batch /home/obs/sys/proc/dbgauss.prc
Condar > get scan_number
Condar > bdrop = 0
Condar > edrop = (h0(noint)+136)/8
Condar > scan_number m1 (to process channel 1; m2 for channel 2)
Condar > dbgauss
```

As with the Continuum Az-El Grid Map, *dbgauss* will do a two-Gaussian fit to your OTF measurement and report the measured beam separation.

The beam separation you measure should be within 5% of the commanded value.

6.3.3 Continuum Sensitivity

Continuum observations at the 12m are usually calibrated by a direct conversion of the measured antenna temperature into flux density (Janskys). The scaling requires that the observer determine the atmospheric zenith optical depth, usually done with a tipping measurement. For a point source, the conversion is given by the standard equation

$$\begin{aligned} S_\nu &= \frac{2kT'_A}{\eta_A A_p} \\ &= \frac{2kT_A}{\eta_A A_p}\exp(\tau_0 A) \\ &= \frac{2kT^*_R}{\eta_A A_p}\eta_l\eta_{fss} \end{aligned} \quad (6.1)$$

where

k is Boltzmann's constant ($1.380662 \times 10^{-23} JK^{-1}$),

T_A is the measured antenna temperature with no efficiency or atmospheric corrections applied,

T'_A is the measured antenna temperature corrected for atmospheric attenuation,

T^*_R is the measured antenna temperature corrected for atmospheric attenuation, radiative loss, and rearward and forward scattering and spillover,

η_A is the aperture efficiency,

A_p is the physical aperture (113.10 m^2 for the 12m),

τ_0 is the zenith optical depth, and

A is the number of airmasses.

The quantity $\frac{2k}{A_p} = 24.4155$ Jy K^{-1} for the 12m.

A convenient measure of sensitivity for continuum observations is the rms flux density per root integration time outside the Earth's atmosphere, S_0. The sensitivity achieved in a given integration time t and under an atmosphere with zenith optical depth τ_0, is given by

$$S = S_0 t^{-1/2} \exp(\tau_0 A) \quad (6.2)$$

A table of S_0 values for key frequencies is given in Table 6.1

Table 6.1: 12m Receiver Continuum Sensitivities

Frequency (GHz)	S_0 (per channel) (Jy s$^{-1/2}$)
90	1.5
145	??
230	6.0

6.3.4 The Digital Backend

The data from all standard continuum observations are processed through the digital backend (DBE). In §3.6.3 we gave a description of the hardware configuration of the DBE. It processes two independent channels and accumulates the signals from four switching phases, defined as:

$$\Phi_1 = \mathsf{SIG} + \mathsf{CAL}$$

$$\Phi_2 = \mathsf{REF} + \mathsf{CAL}$$

$$\Phi_3 = \mathsf{SIG}$$

$$\Phi_4 = \mathsf{REF}$$

where SIG and REF refer, respectively, to the signal and reference positions (+BEAM and −BEAM) of the nutating subreflector. CAL refers to the signal generated by the synchronous noise tube (which is available for 3 mm observations only). If the subreflector is fixed, as in a single-beam, total power measurement, the SIG and REF phases are the same (apart from random noise).

The blanking and delay parameters for the subreflector are set by the Tucson staff regularly. The default switch period is 0.25 seconds (a 4 Hz switch rate), so that the control computer can acquire DBE data in synchronism with its basic timing cycle. The mechanical inertia of the subreflector imposes a limit of about 6 Hz on the maximum switch rate.

When the operator initiates a continuum scan, the control computer issues a signal to the DBE to begin a cycle of four phases. Each time a cycle is completed, the control computer reads the contents of the four phase registers of the DBE. Ideally, this occurs every 500 msec of elapsed time. The presence of error conditions (loss of phase lock or pointing out-of-tolerance) may cause the elapsed time to exceed the specified integration time. If the control computer detects an error condition during phases 1 or 2, it sends a restart signal to the subreflector and the phases are retaken. If the error condition occurs during phases 3 or 4, the computer rejects the entire 500 msec of data. The control system time counter counts down monotonically in 100 msec steps (the monitor updates only every second).

6.3.5 Software Signal Processing of Digital Backend Data

The data sent from the control computer and recorded in the sdd file contain the four phases, integrated over the number of dumps, for each sample or sky position. Thus, the raw data scan contains four times as many points as there were samples. If the sample number is denoted by S_i and phases in that sample as Φ_i, the data are recorded in the order

$$\begin{bmatrix} S_1, \Phi_1 \\ S_1, \Phi_2 \\ S_1, \Phi_3 \\ S_1, \Phi_4 \end{bmatrix} \begin{bmatrix} S_2, \Phi_1 \\ S_2, \Phi_2 \\ S_2, \Phi_3 \\ S_2, \Phi_4 \end{bmatrix} \begin{bmatrix} S_3, \Phi_1 \\ S_3, \Phi_2 \\ S_3, \Phi_3 \\ S_3, \Phi_4 \end{bmatrix} \begin{bmatrix} \ldots \\ \ldots \\ \ldots \\ \ldots \end{bmatrix}$$

No calibration factors have been applied to the data as it is recorded; the data are completely raw counts from the DBE. The raw data are converted into meaningful signals by the analysis program *condar*. The signals that can be computed from the phases are:

Switched Power: $\mathsf{SP} = (\Phi_1 - \Phi_2 + \Phi_3 - \Phi_4)/2$

Total Power: $\mathsf{TP} = (\Phi_1 + \Phi_2 + \Phi_3 + \Phi_4)/4$

Cal Signal: $\mathsf{C} = (\Phi_1 + \Phi_2 - \Phi_3 - \Phi_4)/2$

Zero Level: $\mathsf{Z} = \Phi_1 - \Phi_2 - \Phi_3 + \Phi_4$

Since the data stored in the analysis system are completely raw, there are several calibration parameters used by *condar* which must be set in order to get proper temperature and flux density scaling. Some of these can be set in the control system before you begin data acquisition:

$\mathbf{T}_c$ This is the calibration scale temperature. If the calibration is based on a noise tube, T_c should be the temperature of the noise tube emission. If there is no noise tube, T_c should be set to the value that gives the proper antenna temperature difference between hot and cold loads. T_c has the following standard values:

$$\begin{aligned} T_c &= 400.0 \text{ for single sideband vane calibration,} \\ &= 800.0 \text{ for double sideband vane calibration,} \\ &= 6.0 \text{ for noise tube calibration,} \\ &= \text{ value based on a hot/cold load measurement for fixed calibration.} \end{aligned} \tag{6.3}$$

τ_0 This is the optical depth of the atmosphere at the zenith (in nepers).

The *condar* verbs that manipulate and calibrate DBE data are:

SWITCHED reorders the data array to contain only calibrated switched power data.

TOTALPWR reorders the data array to contain only calibrated total power data.

CALDBE reorders the data array to contain only calibrated calibration values.

ZERO calculates the calibrated rms of the "zero" values and stores the rms in the *condar* array *vrms(1)*.

AVG computes the mean temperature and standard error of the mean of an ON/OFF **sequence**.

In general, you will not need to use these verbs explicitly as resident *condar* procedures (see below) are available for standard displays of switched and total power data.

The way in which the data are calibrated depends upon the type of calibration chosen when you acquired the data. For the three types of calibration available; vane, fixed, and noise tube, the data scaling factors are given by

$$
\begin{aligned}
F_{vane} &= \left(\frac{T_c}{\mathsf{VANE} - \mathsf{SKY}}\right)\exp(A\tau_0) && (6.4)\\
F_{fixed} &= \left(\frac{T_c}{10^4}\right)\exp(A\tau_0) && (6.5)\\
F_{noisetube} &= \left(\frac{T_c}{C}\right)\exp(A\tau_0) && (6.6)
\end{aligned}
$$

where C is the average noise tube calibration signal from each sample, VANE is the signal measured from the vane, SKY is the signal measured from the sky, A is the airmass, and τ_0 the zenith optical depth. T_c is the calibration scale factor defined above.

When using noise tube calibration, the verbs `switched` and `totalpwr` compute a system temperature and store the result in the header under the label *tsys*. The computation of *tsys* is by way of the equation

$$
\begin{aligned}
tsys &= \frac{\Phi_4}{\Phi_2 - \Phi_4} T_c\\
&= \frac{\mathsf{REF}}{\left(\mathsf{REF} + \mathsf{CAL}\right) - \mathsf{REF}} T_c && (6.7)
\end{aligned}
$$

The verbs `switched` and `totalpwr` also calculate a signal-to-noise figure of merit called *tpsn*, which is stored in the adverb *vrms(2)*. *tpsn* is the switched power signal divided by the total power signal and is given by

$$
\begin{aligned}
tpsn &= 0.5 \times \frac{\Phi_1 - \Phi_2 + \Phi_3 - \Phi_4}{\Phi_3 + \Phi_4}\\
&= \frac{\mathsf{SIG} - \mathsf{REF}}{\mathsf{SIG} + \mathsf{REF}} && (6.8)
\end{aligned}
$$

The basic *condar* data reduction commands are given below. #1 is either 1 or 2, for continuum channels 1 or 2. In the `c#1` command below, #1 can be either 1, 2, or b for "both".

```
scan_number get table:  produces a table listing of scan_number
scan_number s#1:  displays a switched power ON/OFF sequence
scan_number m#1:  displays a mapping row
scan_number f#1:  displays a five-point map
scan_number sptip#1:  displays vane-switched tipping scan
scan_number foca#1:  displays a focus-check scan
scan_number c#1:  stacks scans with specified weighting
```

6.4 Observing Procedures

6.4.1 Point Source ON/OFF Observing Procedures

The 12m has available several observing procedures for making ON/OFF measurements, *i.e.*, measurements of the difference between the output powers at a defined point (ON) and a nearby reference position (OFF). These procedures work with the subreflector nutating or not. The ON/OFF procedures are often used for measuring the flux density of weak point sources.

6.4.1.1 The ON/OFF Sequence

The standard point source ON/OFF observing procedure is called a **sequence** in the control system terminology. Using this procedure, the telescope moves between the ON and OFF source positions in the pattern OFF–ON–ON–OFF. A **sequence** is made up of one or more **repeats** of this basic cycle. This order of samples eliminates the effects of linear drifts in atmospheric noise or receiver gain on the measurements. You can specify integration time per position. (Procedures that are simply ONs, OFFs, or an ON–OFF pattern are described below.)

The standard set-up for an ON–OFF **sequence** in beam switched mode is double beam switching (DBS), *i.e.* with the ON and OFF positions separated by the subreflector throw. In this way the radio source to be studied can be cycled between the positive and negative beams by the movement of the telescope. Figure 6.2 displays the positional relationships between the OFF and ON samples. For the DBS mode, the output power difference between the ON and OFF phases is proportional to twice the source flux density. The advantage of the ON–OFF approach is that, to first order, it cancels imbalances between the two beams.

One can, of course, select the OFF position to be different from the position of the −BEAM (or the ON position different from the +BEAM). This is a single beam (SBS) observation. The most frequent use of the SBS mode is to determine the position of the +BEAM and the −BEAM independently, and thereby determine the subreflector throw and orientation.

To perform an ON–OFF **sequence**, you must give the operator the following setup parameters:

(1) The length of time to be spent on each ON or OFF sample and the number of **repeats** of the OFF–ON–ON–OFF cycle. The sample length is usually chosen to be 5 or 10 seconds. This length is usually a good compromise between maximum switching

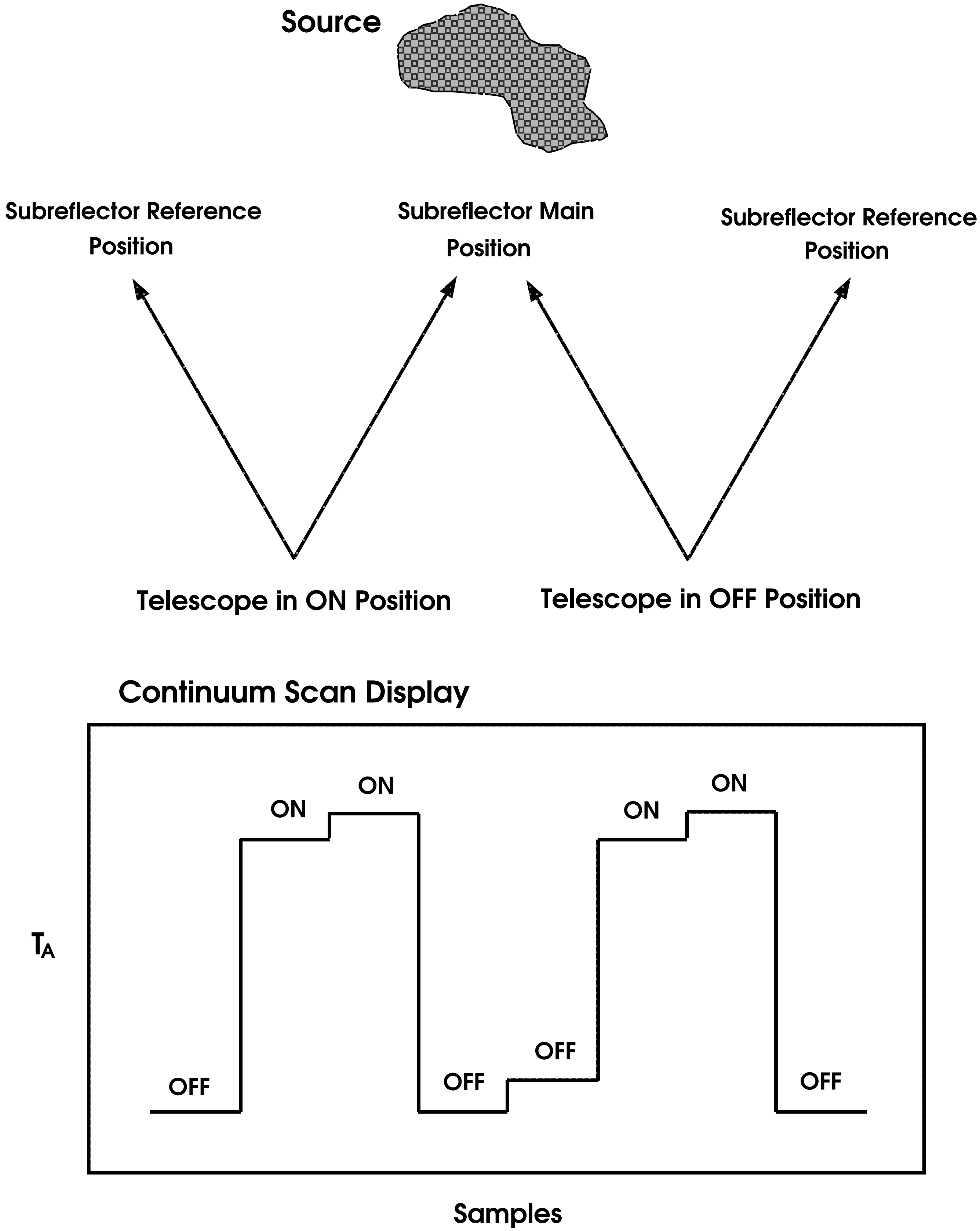

Figure 6.2: Position definitions for continuum sequences.

efficiency of the telescope and the best compensation for atmospheric drifts (the switching pattern corrects for linear drifts and will approximate higher order drifts if the sample time is sufficiently short). The total integration time of a **sequence** is (4 * **seconds** * **repeats**). Thus, if you request 5 **seconds** per sample and 6 **repeats**, the **sequence** takes 120 seconds.

(2) Whether the **sequence** will be made in beam switched mode or position switched (PS) mode. If the observations are in the beam switched mode, indicate whether the Dual Beam (DBS) or Single Beam (SBS) option is in effect (the DBS mode is the normal case).

(3) The required telescope tracking tolerance (TOL), and the optimum pointing positions of the ON and OFF beams (consult the pointing charts at the observer's console).

When you are satisfied that all is in order, ask the operator to begin the scan. These continuum **sequences** can be analyzed using the *condar* procedures described §6.3.5.

6.4.2 Mapping Extended Sources

Two options are available for mapping extended continuum sources: a grid-mapping procedure in which the telescope steps through a rectangular grid in the azimuth/elevation frame and On-The-Fly (OTF) mapping. For a detailed explanation regarding the pitfalls and perils of undersampling in mapping data, see §5.4.6.4.

6.4.2.1 Grid Mapping

In continuum grid mapping, a field is mapped in a rectangular grid in azimuth and elevation relative to the field center. This observing procedure has been developed for use with the dual-beam restoration algorithm of Emerson, Klein, & Haslam (1979 Astr. Ap., 76, 92). It will, however, work satisfactorily for either fixed beam (total-power) mapping or the mapping of fields that are smaller than the subreflector throw via the +BEAM. Note that continuum OTF mapping is functionally the same as continuum grid mapping for most applications. Given the fact that we currently have no analysis software for continuum grid mapping, but have analysis software for continuum OTF, **we recommend that observers use continuum OTF mapping for all continuum mapping experiments**.

The telescope builds a two-dimensional grid of observations by scanning rows at constant elevation relative to the source position. The telescope moves along a row in discrete steps, performing an integration at each position. The grid points are separated in azimuth by real angle. If a map has M columns and N rows the requested field center will lie at the central grid point INT[(M+1)/2], INT[(N+1)/2)] if N and M are odd numbers, where INT denotes an integer truncation. If N and M are even, the requested field center will fall at grid point [(M/2)+1, (N/2)+1]. A scan represents a row of the map in this observing mode. The mean sidereal time of each point is stored in the scan array. Analysis programs have been prepared to combine the scans into two-dimensional maps. You can process these maps using the dual beam restoration algorithm, then transform them into celestial coordinates and stack them. Unfortunately, we do not currently have an implementation of this analysis system at the telescope.

To observe such a map, proceed as follows:

1. Tell the operator whether the data will be taken in total power, fixed beam (total power) or beam switched mode.

2. Give the operator the azimuth and elevation cell sizes, the number of rows and columns, and whether the map will be acquired in dual-beam or single-beam. In a dual beam map, the telescope is positioned so that the azimuth of the center of the map is at the mid-point of the two beams. In a single-beam map, the map is referenced to the +BEAM in azimuth rather than the mid-point between the +BEAM and −BEAM.

6.4.2.2 Continuum On-The-Fly Mapping

The observing setup for continuum OTF mapping is very much the same as it is for spectral line OTF mapping. Continuum OTF data can be processed within . The routines in AIPS use the Emerson, Klein, & Haslam algorithm to restore the dual-beam switched map data. See the AIPS Cookbook chapter which describes continuum OTF data analysis for further information.

6.5 Utility Observing Routines

6.5.1 Sky Tip Procedures

To properly calibrate continuum data, you must correct for the attenuation of the signal as it traverses the atmosphere. We usually determine the atmospheric attenuation from the optical depth at the zenith, τ_0. The total power antenna temperature at a given airmass (elevation) is a function of τ_0 and is given by the equation

$$T_A(sky) = T_{rx} + \eta_l T_m \left[1 - \exp(-\tau_0 A)\right] + (1 - \eta_l) T_{spill} + \eta_l T_{bg} \exp(-\tau_0 A), \qquad (6.9)$$

where T_{rx} is the receiver noise temperature, η_l is the "warm spillover" efficiency (rear spillover, scattering, blockage, and ohmic loss efficiency), T_m is the mean atmospheric temperature, τ_0 is the atmospheric optical depth at the zenith, A is the airmass, T_{spill} temperature of the warm spillover, and T_{bg} is the temperature of the cosmic background radiation. Note that T_m, T_{spill}, and T_{bg} are actually equivalent Rayleigh-Jeans temperatures of the point on the Planck blackbody curve corresponding to the same frequency. This correction factor is given by

$$J(\nu, T) = \frac{h\nu}{\exp\left(\frac{h\nu}{kT}\right) - 1}, \qquad (6.10)$$

Table 6.2: Sky Tip Antenna Positions

Step	Elevation (°)	Airmass
1	22.62	2.6
2	25.77	2.3
3	30.00	2.0
4	36.03	1.7
5	45.58	1.4
6	65.38	1.1
7	45.58	1.4
8	36.03	1.7
9	30.00	2.0
10	25.77	2.3
11	22.62	2.6

where ν is the observing frequency, T is the kinetic temperature, and h and k are the Planck and Boltzmann constants, respectively. For simplicity, we will retain the symbol "T" for temperatures, but in calculations "T" should be replaced by "J(ν,T)".

The opacity of the atmosphere at the zenith, τ_0, is usually determined by measuring the T_A(sky) at several elevations and fitting the results with some form of Equation 6.9. The mean atmospheric temperature and the spillover temperature are usually ~0.95 - 0.97 of the ambient temperature.

The basic observing procedure for measuring τ_0 is called an **sptip**. This procedure steps the telescope through a series of elevation angles, moving from low to high elevation, and then back to low. The precise elevations, in steps of 0.3 airmasses, are listed in Table 6.2. In an **sptip**, the system makes total power observations of both the sky and the ambient temperature absorbing vane at each position in Table 6.2. Both sky and vane temperatures are recorded for analysis.

To perform an **sptip** observation, simply ask the operator to slew the telescope to an azimuth near your program source position and start the measurement. The *condar* data analysis package contains two methods of analyzing an **sptip**. If you wish on-line atmospheric corrections to be applied to continuum data displays, ask the operator to enter the new value of τ_0. Remember that the atmospheric absorption changes with time, and if the highest accuracy is required, a small correction should be applied off-line using all the opacity data for the run to interpolate the most-probable value for each scan.

6.5.1.1 The SPTIP Analysis Procedure

The *sptip* data reduction procedure uses the difference between vane and sky temperatures to derive τ_0. This is the simplest of all the tip analysis routines: it requires no input parameters, does not require accurate calibration of the temperature scale, nearly always produces at least a first order approximation to the optical depth, but makes a number of simplifying assumptions that may diminish its accuracy.

The antenna temperature of the sky is given in Equation 6.9, while the antenna temperature of the vane is given by

$$T_A(vane) = T_{rx} + T_{vane} \tag{6.11}$$

where T_{vane} is the Rayleigh-Jeans-equivalent temperature of the vane (generally the ambient temperature). The difference between vane and sky temperatures is thus

$$T_{v-s} = T_{vane} - \eta_l T_m \left[1 - \exp(-\tau_0 A)\right] - (1 - \eta_l) T_{spill} - \eta_l T_{bg} \exp(-\tau_0 A). \tag{6.12}$$

The SPTIP analysis procedure makes the following assumptions:

$$\begin{aligned} T_{vane} &= T_m = T_{spill} = T_{amb}, \\ \eta_l &= 1, and \\ T_{bg} &= 0 \end{aligned} \tag{6.13}$$

where T_{amb} is the Rayleigh-Jeans-equivalent ambient temperature. Under these assumptions, one then finds that

$$\ln(T_{v-s}) = \ln(T_{amb}) - A\tau_0. \tag{6.14}$$

From the measured array of T_{v-s} as a function of A, the *sptip* procedure fits for τ_0 by linear least squares. Among the assumptions 6.13, the assumptions that $J_m = J_{amb}$ and that $\eta_l = 1$ are the most inaccurate. In addition, because the calibration scale is not always in calibrated in Kelvins, the term $\ln(T_{amb})$ in Equation 6.14 is fit as a free parameter. This gives τ_0 more freedom than it ought to have.

Experience with the *sptip* routine has shown that although it is the easiest of the available routines to use, it suffers from two deficiencies: (1) it tends to underestimate τ_0, especially for large values of τ_0, and (2) it often appears to give a misleadingly good fit, *i.e.* it may indicate that the atmosphere is more stable than it really is. Nevertheless, under moderately low τ_0's (say <0.3), the *sptip* procedure usually gives an acceptably good measure of the atmospheric optical depth.

To use the *sptip* analysis procedure, in *condar* type:

```
Condar > scan_number sptip#1
```

where #1 is either 1 or 2 to choose channel 1 or channel 2. The data and fit are displayed in Figure 6.3

6.5.1.2 The STIP Reduction Procedure

The *stip* reduction procedure fits Equation 6.12 to the data from an **sptip** observation by way of nonlinear least squares. This procedure is the most direct of the two tipping analysis options: it makes no assumptions other than the accuracy of the basic model (Equation 6.9). To give an accurate measure of τ_0, it does have several stringent requirements:

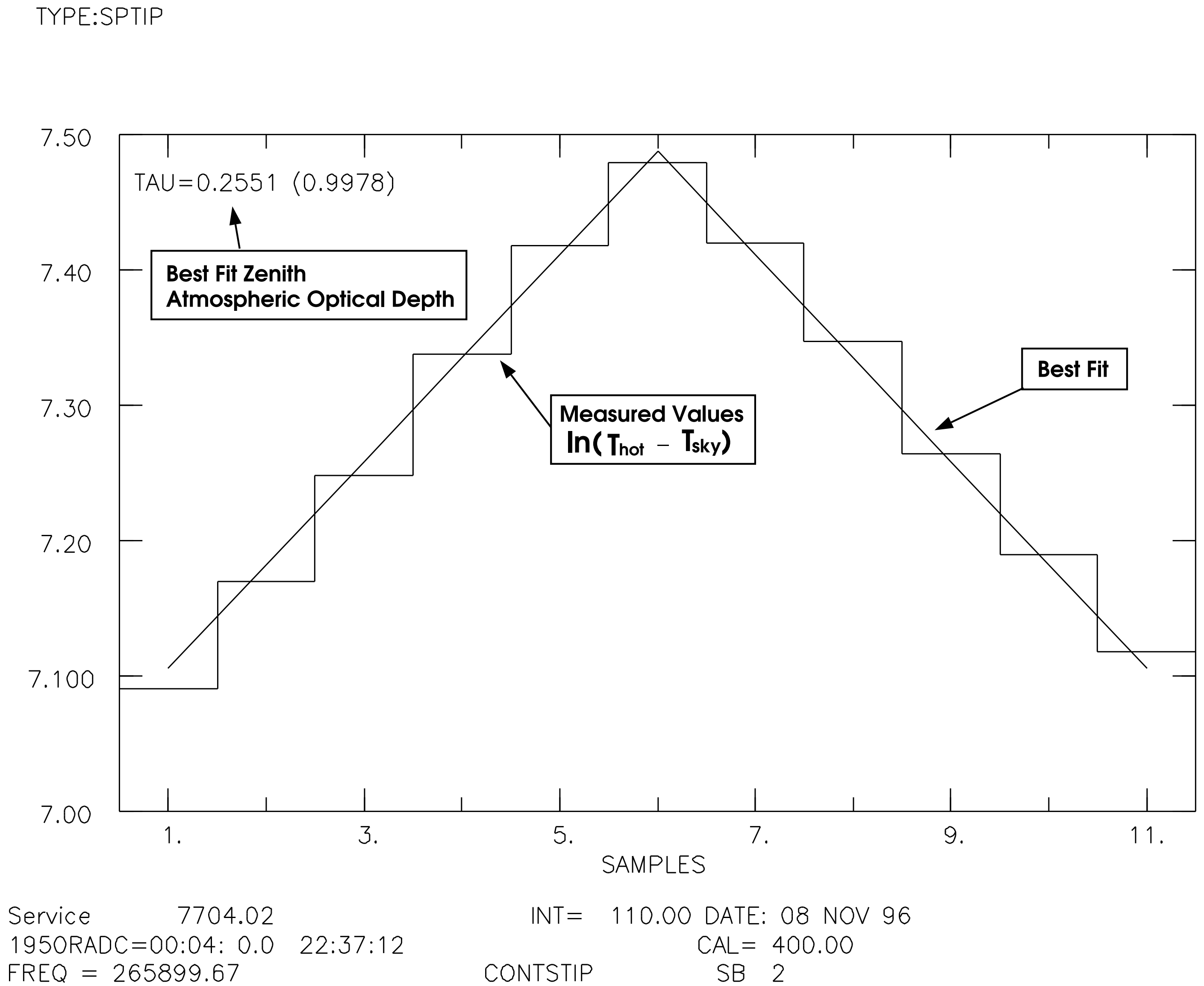

Figure 6.3: Sample SPTIP tipping scan.

1. The temperature scale must be accurately calibrated, which means that you must do a hot/cold load measurement to determine the value for T_c in the "fixed" calibration method (see §6.6.2);

2. You must supply several input parameters, including $\frac{T_m}{T_{amb}}$ (called *ftm* in *condar*) and $\frac{T_{spill}}{T_{amb}}$ (called *ftsbr* in *condar*).

The *stip* procedure can also be used to fit for η_l, a basic efficiency factor. Because it is a nonlinear (hence iterative) fitting routine, it may not converge if the data are of poor quality or, conversely, it may converge to a nonsensical result. Use *stip* with caution. To analyze an **sptip** scan with *stip* in *condar*:

```
Condar > scan_number stip
```

If you want to solve for η_l, set *etafree*=1 in *condar* (*etafree*=0 by default). Figure 6.4 shows what the *stip* output looks like.

6.6 Calibration

To accurately calibrate continuum data, you must set the temperature scale and/or flux density scale, correct for atmospheric attenuation, and correct for telescope systematics such as the gain-elevation effect. The method currently used to calibrate 12m continuum data is called "vane calibration".

6.6.1 Vane Calibration

Calibration of the antenna temperature scale for continuum data is accomplished using the vane calibration technique (see §5.6.1). In addition to a calibration of the antenna temperature scale, absolute calibration of continuum data also requires a measurement of the aperture efficiency or a factor for converting from antenna temperature to flux density. It may also be necessary to apply a correction for the gain-elevation effect if it is important at the particular observing frequency. To calibrate continuum data, follow the steps outlined below.

1. Perform a hot/cold load calibration to determine the receiver noise temperature and to set the temperature scale. The procedure for making a hot/cold measurement is described in detail in Section 6.6.2. This measurement will produce a value for T_c, the calibration scale factor, which is required by the data analysis routines to scale the data.

2. Perform a calibration cycle (called a CALIBRATE) at intervals which you prescribe. The interval should be small enough that the atmospheric transmission during the interval does not change appreciably. This depends on the atmospheric optical depth and its stability and the elevation. During stable conditions of low optical depth, a CALIBRATE every 10-15 minutes is usually sufficient. If the atmosphere is choppy or the elevation is changing rapidly as when the source is rising or setting, more frequent CALIBRATEs may be necessary. The operator can command the system to perform

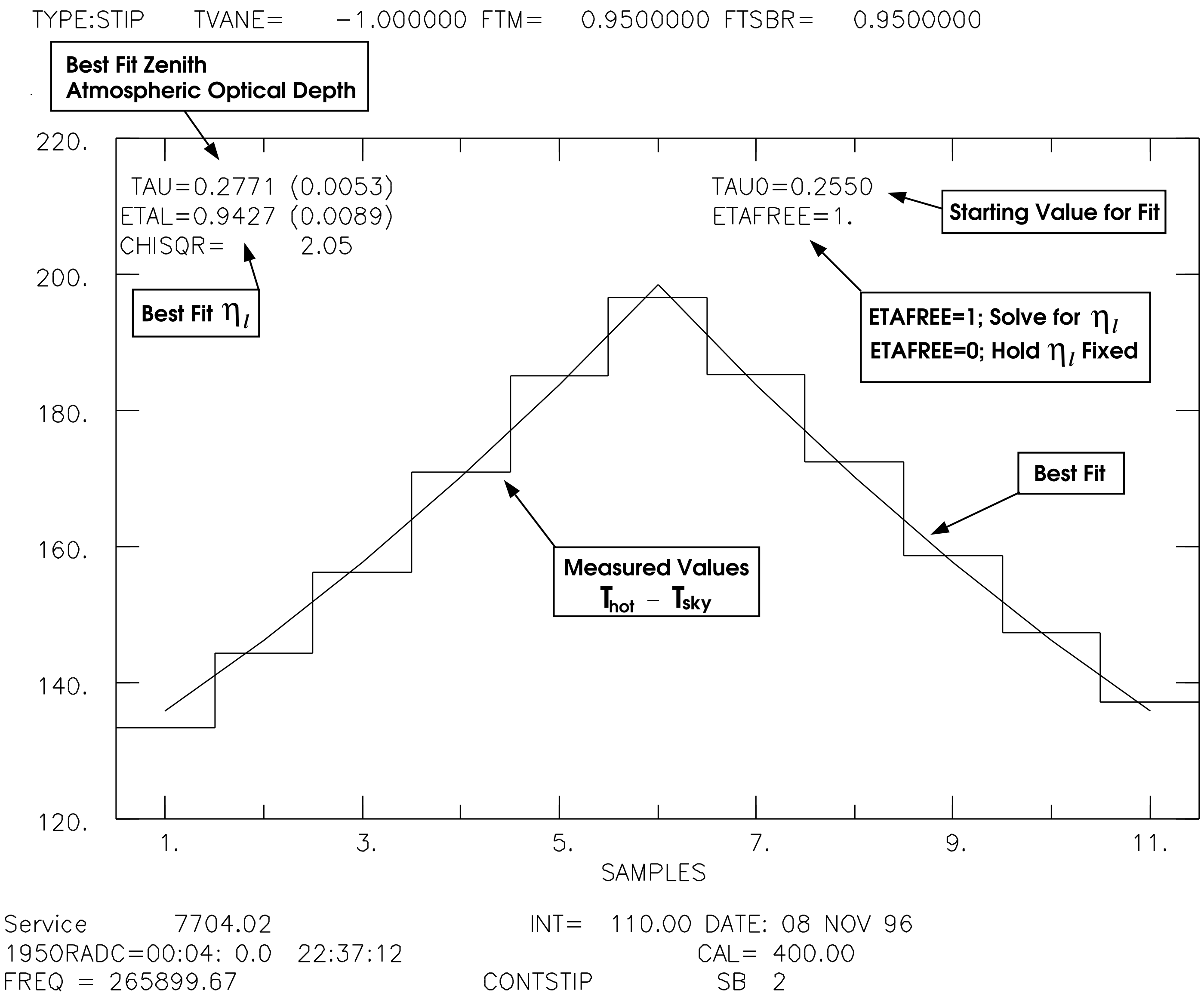

Figure 6.4: Sample STIP tipping scan.

a CALIBRATE before each continuum scan or before a specified block of scans. The length and number of repeats of a given CALIBRATE can also be specified. The default is 30 seconds, with the vane and sky sampled 15 times each at 1 second per sample.

3. Observe discrete astronomical sources to calibrate the telescope pointing and set a flux density scale for the data. The measurement can be used to enter a value of the aperture efficiency (η_A). The aperture efficiency is used by the data reduction routines to convert antenna temperature to flux density. The observations of calibration sources should be repeated frequently during the course of the observing run. A calibration curve, plotted as a function of time, can be used for the most accurate adjustment of the flux density scale in the final analysis.

Many observers choose to skip the measurement of the temperature scale by hot/cold loads and calibrate their data strictly by comparisons with standard sources. In this relative calibration method, one merely observes a succession of standard sources, forms a calibration curve of flux density conversion factors, and through interpolation, corrects the data after the run is over.

6.6.2 Hot/Cold-Load Calibration

A hot/cold load calibration can be used to set the continuum temperature scale, to measure the receiver noise temperature, the noise tube temperature, the sky temperature, and the atmospheric optical depth. At present, we perform hot/cold loads by manually inserting hot and cold loads into the beam and measuring the deflections through the computer, on digital voltmeters, and sometimes on the analog chart recorders. The cold load usually consists of a styrofoam box holding a square of microwave absorber immersed in liquid nitrogen. The vaporization temperature of liquid nitrogen at the elevation of the 12 Meter Telescope is 80 K. For frequencies below about 230 GHz, we recommend that you use this temperature. For higher frequencies, the styrofoam may begin to absorb the radiation and will add to the temperature of the load. At these high frequencies, we recommend that you use another type of cold load known as a "dipper". The dipper consists of a funnel-shaped box lined with absorber on the end of a wooden handle. The dipper is dipped into liquid nitrogen and held over the receiver feed during cold load cycles. A hot/cold measurement requires the active participation of the operator and at least one observer. To perform a hot/cold load calibration with a coherent receiver, proceed as follows:

1. The operator must drive the telescope to the zenith position and open the dome door to 90°.

2. Set the observing parameters for a **continuum on/off sequence**. Use a 1 second sample time with a scan time of 300 seconds (5 minutes), which is equivalent to 75 repeat cycles. This should be an adequate amount of time to make all of the necessary measurements.

3. Set the calibration mode to "fixed" with a calibration temperature value of 1.0.

4. The operator should then fill the cold load box with liquid nitrogen and carry it to the receiver bay. The ambient temperature vane can be used as the hot load.

5. On the continuum receiver control rack, switch the leftmost thumbweels on the IF attenuators of both channels to 1, giving >100 dB of attenuation. This will provide the zero point measurement at the start of the scan.

6. Start the **sequence**. Measure the zero point levels for about 10 seconds. Don't forget to take this attenuation out when you are done doing your zero point measurement. Then, by speaking over the intercom to the telescope, have the operator insert the cold load, and leave it in place for about 20 seconds. Note the voltages on the digital voltmeters on the continuum IF chassis. Ask the operator to remove the cold load and switch the ambient vane in for about 20 seconds, and note the voltages. The vane is controlled from the "Chopper Control" chassis in the control room. Perform 3 cycles of HOT/COLD measurements.

7. After the HOT/COLD measurements, ask the operator to move away from the beam and measure the sky voltage. If the noise tube is not in use, let the scan run out with the telescope looking at blank sky. If you wish to measure the noise tube emission, switch the tube on using the modulate switch on the subreflector control chassis, and note the voltages. You may wish to make several OFF/CAL measurements before the scan ends.

To process the HOT/COLD measurement, in *condar*:

```
Condar > scan_number hc
```

The `hc` procedure will prompt you for the hot load temperature in Celsius and the cold load temperature in Kelvins. If the observation was made in double sideband mode, give the frequency of the local oscillator. The hot load temperature should be the temperature of the vane; the vane temperature is displayed on the "Chopper Control" chassis in the control room. After entering these data, the crosshairs will appear on the graphics screen and you will be prompted to mark the zero offset, the cold load, and hot load samples. The procedure will then prompt you to enter any sky and noise tube samples that may exist. Ask the operator to update the value of T_c calculated by `hc` for the type of calibration, fixed or noise tube, that you are using.

If you wish to reduce the data by hand, you can get a table of the numbers in the scans by typing

```
Condar > scan_number table
```

In addition to the computer scan, you should reduce the data obtained from the voltmeters (or chart recorders) for comparison. The formulae for the quantities of interest are given below. The receiver noise temperature is a function of the "Y-factor", defined by

$$Y = \frac{V_{hot}}{V_{cold}} \tag{6.15}$$

where V_{hot} is the measured hot load voltage less the zero offset voltage, and V_{cold} is the measured cold load voltage less the zero offset voltage. The receiver noise temperature T_{rx} is then given by

$$T_{rx} = \frac{T_{hot} - YT_{cold}}{Y - 1} \tag{6.16}$$

where T_{hot} and T_{cold} are the equivalent Rayleigh-Jeans effective temperatures of the hot and cold loads, respectively, given by Equation 6.10. The Kelvins per volt, KPV, of the continuum system is given by

$$KPV = \frac{T_{hot} - T_{cold}}{V_{hot} - V_{cold}} \tag{6.17}$$

The Rayleigh-Jeans equivalent sky temperature is given by

$$T_{sky} = (V_{sky} - V_{cold}) \times KPV + T_{cold} \tag{6.18}$$

where T_{cold} is the equivalent Rayleigh-Jeans temperature of the cold load given by Equation 6.10. If a noise tube was measured, its temperature is given by

$$T_{nt} = (V_{nt} - V_{sky}) \times KPV \tag{6.19}$$

where T_{nt} is the Rayleigh-Jeans equivalent temperature of the noise tube and V_{nt} is the measured voltage of the noise tube. The optical depth of the atmosphere at the zenith is, from Equation 6.9

$$\tau_0 = -\frac{1}{A} \ln \left[\frac{T_A(sky) - T_{rx} - \eta_l T_m - (1 - \eta_l) T_{spill}}{\eta_l (T_{bg} - T_m)} \right], \tag{6.20}$$

where A = 1 if the observation is at the zenith.

Equations 6.15 through 6.20 are used in the *condar* procedure `hc` and can be used to reduce the computer data manually if you so choose. If you are using a noise tube, use the value of T_{nt} given by Equation 6.19 for the calibration scale factor, T_c, entered into the control system. If you are not using a noise tube, the value of T_c to use is given by

$$T_c = \frac{T_{hot} - T_{cold}}{T_A(hot) - T_A(cold)} T_c(old\ value), \tag{6.21}$$

where T_{hot} and T_{cold} are the Rayleigh-Jeans equivalent hot and cold load temperatures, $T_A(hot)$ and $T_A(cold)$ are the apparent antenna temperatures of the hot and cold loads, respectively, and $T_c(old\ value)$ is the old value of T_c that was in the computer during the hot/cold measurement. For each channel, there should be good consistency between the values computed via the computer and the voltmeter.

If you are using a noise tube to calibrate the data, the calibration scale should stay fairly accurate even if the gain of the receiver changes slightly. If you are not using a noise tube, the T_c's and noise temperatures are accurate only at the moment they are measured: receiver gain and tuning drifts will change these parameters. Depending on your choice of calibration methods, you may need to repeat the HOT/COLD measurements frequently.

Table 6.3: Planetary Flux Density Standards

Planet	T_B(90 GHz) (K)	T_B(150 GHz) (K)	T_B(227 GHz) (K)	Unit Semi-Diameter (arcsec)
Venus	367±10	294±22	317±30	8.34
Mars	207±6	210±10	207±7	4.68
Jupiter	172±1	173±1	171±4	95.20
Saturn	149±4	137±11	140±14	78.15
Uranus	135±4	112±5	98±5	35.02
Neptune	130±5	107±5	93±5	33.50

6.6.3 Calibration of the Flux Density Scale

For most continuum observations, the flux density scale is calibrated by observations of standard radio sources. In doing this, it should be remembered that, in addition to corrections for receiver and atmospheric effects, you should allow for the gain-elevation properties of the telescope if the observations cover a significant range of elevations. Current gain-elevation curves are given in *The NRAO 12m Telescope Equipment and Calibration Status* document.

At millimeter wavelengths, the flux densities of most extragalactic sources are variable and we recommend the use of the planets or compact HII regions for calibration. At least at 1mm, the brightest planets are usually significantly resolved. The peak flux densities of the planets should be computed using the `planets` utility program available on any of the mountain workstations. This program needs to know the effective observing frequency (GHz), the telescope HPBW (arcsec), the planetary unit semi-diameter in arcseconds (*i.e.* the semi-diameter of the planet as seen from a distance of 1 AU, available from the Astronomical Almanac or Table 6.3), the geocentric distance of the planet (AU), available from the Astronomical Almanac, and the brightness temperature of the planet at this frequency. The result is given in Jy/beam.

Table 6.3 gives the recommended brightness temperatures of the planets at 90, 150, and 227 GHz. Most of these are taken from the work of Ulich *et al.*, Griffin *et al.*, and Hildebrand *et al.*. The brightness temperature of Mars depends on solar distance. At 90 GHz, Ulich (1981, AJ, 86, 1619) suggests an effective temperature for Mars of

$$T_B(90GHz) = 206.8 \left[\frac{1.524}{R_0}\right]^{\frac{1}{2}} K, \tag{6.22}$$

where R_0 is the Mars-Sun distance in AU.

Some other radio sources are expected to be non-variable, and in the case of HII regions, unpolarized. Peak flux densities for sources measured with the 12 Meter Telescope that make suitable flux density calibrators at 90 GHz are given in Table 6.4.

Table 6.4: Flux Density Calibrators

Source	S(90 GHz) (Jy)
DR21	14.5±0.7
W3(OH)	3.8±0.3
3C274 (Virgo A)	6.5±0.3

6.7 Continuum Status Monitor

A sample continuum status monitor display is shown in Figure 6.5. Each numbered box in Figure 6.5 indicates a section of the display which describes a particular set of attributes of a continuum measurement:

Box 1: Scan number, source name, and timing information.

- **SCAN:** Current scan number.
- **SOURCE:** Source name.
- **HORIZON:** Time to 15° elevation (rise or set).
- **LST:** Current local sidereal time.
- **UTC:** Current coordinated universal time.
- **DUT1:** UT1-UTC time correction.
- **date:** Current year (top) and date (bottom).
- **OBS:** Current observer initials (top) and data file number (bottom).
- **OPR:** Current operator initials.

Box 2: RA/Dec and lII/bII position information.

- **TOTAL:** Current total (apparent plus offsets) RA and Dec.
- **B1950.0:** Current Equinox B1950 RA and Dec.
- **APPARENT:** Current apparent RA and Dec.
- **GALACTIC:** Current lII and bII.
- **OFFSET:** Current applied RA and Dec offsets.

Box 3: Apex position information.

- **NS:** North (top) and south (bottom) focus translation stage offset position in millimeters.
- **EW:** East (top) and west (bottom) focus translation stage offset position in millimeters.

Box 4: Azimuth and elevation position and pointing offset information.

COMMAND: Commanded azimuth and elevation (spherical coordinate conversion plus pointing corrections).

ACTUAL: Actual azimuth and elevation encoder readings.

ERROR: Difference between COMMAND and ACTUAL azimuth and elevation.

OFFSET: Total azimuth and elevation offsets (sum of pointing offsets plus subreflector beam throw).

POINT: Azimuth and elevation pointing model corrections.

PSREF: Reference position offset in azimuth and elevation.

Box 5: Receiver calibration and tipper information.

ATM: Number of air masses toward current elevation.

RCVR: Receiver name.

RBAY: Receiver bay.

F0: Axial focus zero position in millimeters.

TC: Calibration scale factor for receiver channels 1 (top) and 2 (bottom).

TAU0: Actual (top) and 225 GHz (bottom, measured continuously using a tipping radiometer) zenith opacity.

FWHM: Beam FWHM (top) and HWHM (bottom, used for five-point measurements) in mm:ss.

TSYS: Channel 1 (top) and 2 (bottom) system temperatures in K.

MM_H2O: Millimeters of water vapor at zenith based on the 225 GHz tipping radiometer measurement of τ_0 and a conversion of 1 millimeter H_2O equals an opacity of 0.05 at 225 GHz.

Box 6: Subreflector beam and quadrant detector position information.

+BEAM: Azimuth and elevation position for the +Beam in mm:ss.

-BEAM: Azimith and elevation position for the −Beam in mm:ss.

QX: Quadrant detector x-axis position in millimeters.

QY: Quadrant detector y-axis position in millimeters.

Box 7: Frequency, velocity, and calibration information.

WL: Focus step size used for focus measurements in millimeters.

OBJ_V: Source velocity in chosen reference frame in km/s.

ANT_V: Antenna velocity in chosen reference frame in km/s.

CAL: Calibration type.

%EFF: Aperture efficiency.

SB: Signal sideband (upper or lower) for channel 1 (top) and channel 2 (bottom).

LO: Local oscillator multiplication factor.

IF'S: Intermediate frequencies in MHz.

FREQUENCY: Rest frequencies for channels 1 (line 1) and 2 (line 2), in GHz, with their associated LO synthesizer frequencies (lines 3 and 4, respectively), in MHz.

DBE_RUN: Current observing mode.

Box 8: Telescope tracking and weather information.

TOL: Input and actual tracking tolerance in m:ss.

FOCUS: Input and actual axial focus at the current elevation in millimeters.

TORR: Barometric pressure in Torr.

%RH: Relative humidity.

T_AMB: Ambient temperature in C.

REFRT: Input and actual refraction constant for elevation refraction pointing correction in arcseconds.

Box 9: Current observation scan and integration time information.

MODE: Observing mode.

SCANS: Number of scans requested.

SAMPLES: Number of continuum on/off samples requested.

SEC: Total (top) and remaining (bottom) sample time in seconds.

TIME: Total (top) and remaining (bottom) integration time for this scan in mm:ss.

```
1
SCAN     SOURCE    HORIZON      LST        UTC            DUT1    1996   OBS  OPR
 7705  Mars            6:57    8:49:53  13:04:21        -0.011   08 Nov  sys  VLG
RNAME                                   13:04:21                          289

2                                                      3
                R.A.          DEC.                     APEX
TOTAL       10:30:06.5   11:15:35.7                 NS +0.500
B1950.0      0:00:00.0    0:00:00.0                    +0.515
APPARENT    10:30:06.5   11:15:35.7                 EW +0.000
GALACTIC     133.94746      1.06432                    +0.000
OFFSET       0:00:00.0    0:00:00.0

4
               AZIMUTH      ELEVATION
COMMAND   126:18:18.9     58:59:36.6
ACTUAL    126:18:18.2     58:59:36.6
ERROR       0:00:00.7      0:00:00.0
OFFSET      0:00:00.0      0:00:00.0

POINT       0:00:14.3    -0:00:20.5
PSREF       0:00:00.0      0:00:00.0

5
 ATM    RCVR  RBAY  F0    TC     TAU0   FWHM   TSYS
 1.17   1mmhi  4  43.3 400.0   0.223  0:30    690
MM_H2O-> 2.54          400.0   0.127  0:15    670

6
+BEAM   1:00  0:00   QX -6.36
-BEAM  -1:00  0:00   QY +5.20

7
 WL          OBJ_V ANT_V  CAL   %EFF SB   LO IF'S    FREQUENCY
0.60         -14.7  -0.3 Vane    32  USB   3  100    265.886432
                                     USB     1500    265.886432
                           DBE_RUN                  1956.293860
                                                    1956.293860

8
         TOL  FOCUS  TORR  %RH  T_AMB  REFRT
INPUT    0:05  45.7   613    3   13.4  46.2
ACTUAL   0:00  45.6   WIND-> 114 @ 21  46.2

9
MODE SCANS  SAMPLES   SEC    TIME
QK5     4       40    7.0    4:40
                 0    0.0    0:00
```

Figure 6.5: Continuum status monitor display. The numbered boxes indicate sections of information on the display which are explained in §6.7

Appendix A

Pointing Equations for the 12m Telescope

A.1 Primary Pointing Equations

The basic pointing model in use at the 12m is much the same as that described by Stumpff (1972, Kleinheubacher Berichte, 15, 431) and Ulich (1981, Int. J. Infrared & Millimeter Waves, 2, 293). The azimuth and elevation terms used to correct the nominal encoder positions are given by the equations

$$\begin{aligned} \Delta A &= IA + CA\sec(E) + NPAE\tan(E) + AN\tan(E)\sin(A) \\ &\quad - AW\tan(E)\cos(A) + A_{obs}\sec(E) \qquad \text{(A.1)} \\ \Delta E &= IE + ECEC\cos(E) + AN\cos(A) + AW\sin(A) + E_{obs} + R_0 f(E) \qquad \text{(A.2)} \end{aligned}$$

where A and E are the azimuth and elevation of the source and

AI is the azimuth encoder zero offset,

CA is the collimation error of the electromagnetic axis,

$NPAE$ Non-perpendicularity between the mount azimuth and elevation axes,

AN is the azimuth axis offset/misalignment north-south,

AW is the azimuth axis offset/misalignment east-west,

A_{obs} is the observer-applied azimuth correction,

ΔE is the total elevation encoder correction,

IE is the elevation encoder zero offset,

$ECEC$ is the gravitational flexure correction at the horizon,

E_{obs} is the observer-applied elevation correction,

R_0 is the weather dependent term to the atmospheric refraction correction,

$f(E)$ is the elevation dependence of the atmospheric refraction correction.

The weather-dependent refraction coefficient, which is practically independent of wavelength, is given by Liebe & Hopponen (1977, IEEE Trans. Antennas Propagation, AP-25, 336, equation 9) as

$$\begin{aligned} N_0 &= (n-1) \times 10^6 \\ &= R_0(radians) \times 10^6 \\ &= 103.56\frac{P_d}{T_s} + 95.5\frac{P_w}{T_s} + 499500\frac{P_w}{T_s^2} \quad ppm \end{aligned} \tag{A.3}$$

and is given similarly by Crane (in *Methods of Experimental Physics*, volume 12, part B, page 186, equation 2.5.1) as

$$N_0 = 103.43\frac{P_d}{T_s} + 96.0\frac{P_w}{T_s} + 499835\frac{P_w}{T_s^2} \quad ppm \tag{A.4}$$

where I have ignored the partial pressure contribution due to carbon dioxide (only $\sim$ 0.03% of the total pressure), n is the complex index of refraction, and the pressures and temperatures are as defined below. A similar expression to the two given above can also be found in Allen (1963, "Astrophysical Quantities", page 120). Taking the Liebe & Hopponen relation (Equation A.3) for N_0 and solving for R_0 in arcseconds yields

$$R_0 = 21.36\frac{P_s}{T_s} - 1.66\frac{P_w}{T_s} + 103029.27\frac{P_w}{T_s^2}, \tag{A.5}$$

where

P_d is the partial pressure of dry gases in the atmosphere (in Torr),

P_w is the partial pressure of water vapor at the surface (in Torr),

P_s is the total surface barometric pressure (in Torr), which is equal to $P_d + P_w$, and

T_s is the surface ambient air temperature (in Kelvin).

P_s must be measured by a barometer at the telescope site. P_w may be calculated from the expression

$$P_w = RH\frac{e_{sat}}{100}, \tag{A.6}$$

where RH is the surface relative humidity (in percent) and e_{sat} is the surface saturated water vapor pressure (in Torr) and is given by Crane (in *Methods of Experimental Physics*, volume 12, part B, page 187, equation 2.5.3) as

$$\log(e_{sat}) = 24.67 - \frac{2990.14}{T_s} - 5.31\log(T_s). \tag{A.7}$$

Note that Ulich (1981) quotes a similar expression for $\log(e_{sat})$, but does not give a reference.

The weather-dependent term R_0 is calculated using the on-site weather station, and is recalculated every time the surface temperature changes by more than 1.5°, the surface relative humidity changes by more than 5%, or the surface barometric pressure changes by more than 1 Torr. R_0 usually remains in the range 48″ to 60″. A plot of R_0 as a function of T_s and relative humidity for a constant total surface barometric pressure is shown in Figure A.1. The elevation dependence of the refraction correction is given by

$$f(E) = \frac{\cos(E)}{\sin(E) + 0.00175\tan(87.5 - E)}. \tag{A.8}$$

This term is recomputed for each elevation of observation.

The 12m staff determines the pointing coefficients regularly. To derive a new pointing model a campaign of optical and radio pointing sources measurements are made. Both the optical and radio pointing sources are observed at as many azimuth and elevation positions as possible and the corrections necessary to receive peak flux from the sources are measured. The corrections are then input to a fitting program and the coefficients are determined. The total rms of the fit is typically 3″– 5″.

A.1.1 Secondary Pointing Corrections

In addition to the primary pointing corrections, a set of secondary pointing corrections are used at the 12m. In azimuth, these corrections are given by the equation

$$\Delta A_1\cos(E) = IA_1\cos(E) + CA_1, \tag{A.9}$$

where the left-hand side of the equation corresponds to the "cross-elevation" azimuth correction on the sky, given at a particular elevation by the observer-applied azimuth correction. In elevation, the secondary correction is

$$\Delta E_1 = ECEC_1\cos(E) + IE_1, \tag{A.10}$$

These terms correspond to the linear (in $\cos(E)$) terms in the principal pointing equations given above: A_1 is the supplemental azimuth encoder offset, C_1 is the supplemental electromagnetic collimation error correction, B_1 is the supplemental gravitational bend error, and E_1 is the supplemental elevation encoder offset.

Each of the four receiver bays have their own set of these secondary coefficients to compensate for slight differences between feed and mirror alignments in each bay. The intent of these pointing coefficients is to keep the required pointing offsets as close to zero as possible. The determination of these coefficients requires much less data than the main pointing equations and can thus be adjusted on a more frequent basis.

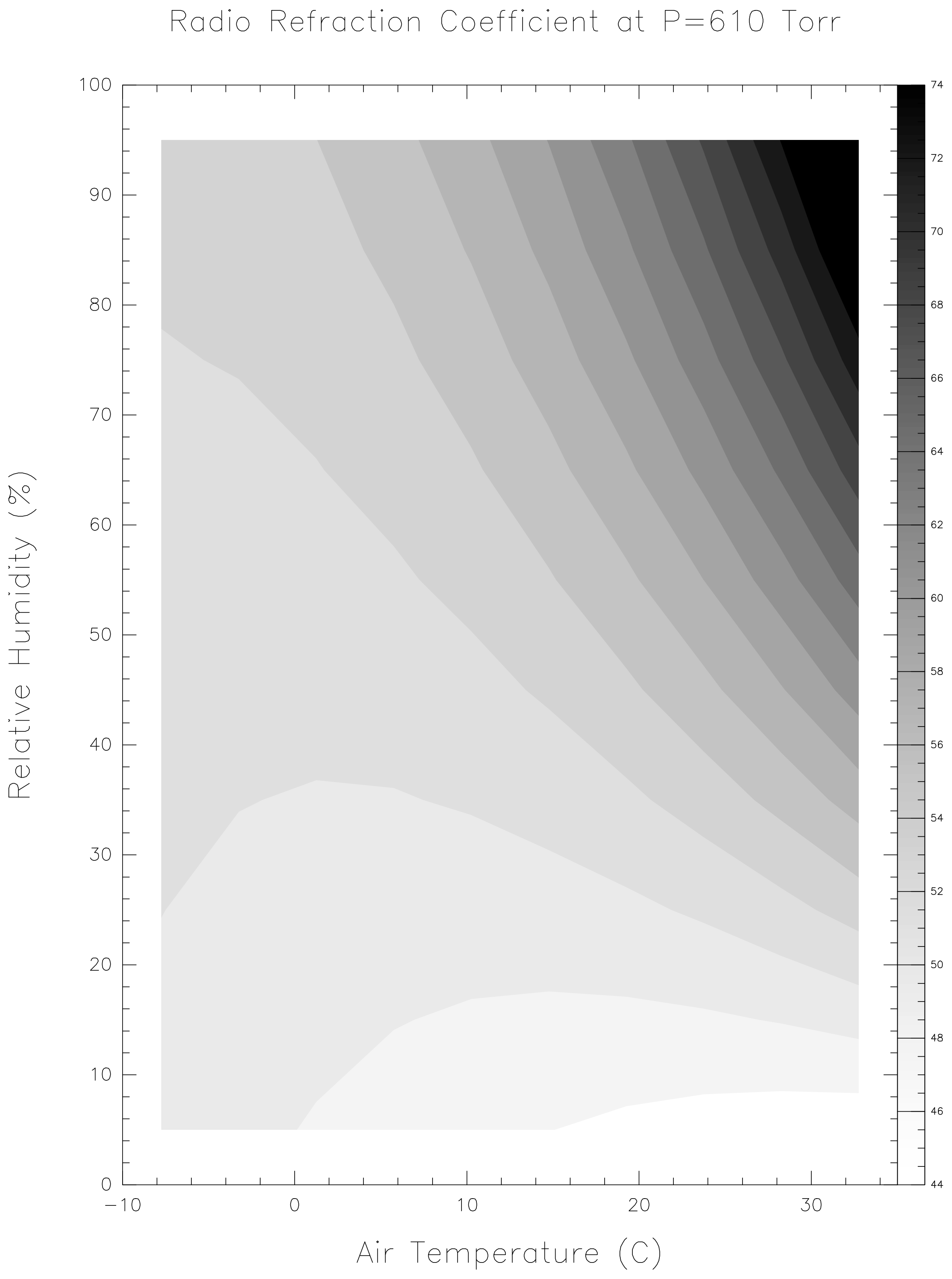

Figure A.1: R_0 as a function of T_s and relative humidity for a constant total barometric pressure of 610 Torr.

Appendix B

The Relationship Between Flux and Brightness Temperature

In the following I derive the relationship between the flux of a source and its brightness temperature for a gaussian beam measuring two different source geometries, uniform disk and gaussian. The general relation between flux and brightness temperature is

$$S_\nu = \frac{2k}{\lambda^2} \int T_B(\Omega) d\Omega \tag{B.1}$$

Note that throughout this discussion when I refer to a "temperature" I am actually referring to the effective source radiation temperature $J(\nu, T)$, which is defined by Equation C.1.

B.1 Uniform Disk Source

$$\begin{aligned} S_\nu &= \frac{2k}{\lambda^2} \int_0^{R_p} 2\pi r \left(T_p - T_{bg} \right) \left\{ \exp\left[-4 \ln(2) \left(\frac{r}{\theta_B} \right)^2 \right] \right\} dr \\ &= \frac{2k(T_p - T_{bg})}{\lambda^2} \frac{\pi \theta_B^2}{4 \ln(2)} \left\{ 1 - \exp\left[-\ln(2) \left(\frac{\theta_{eq}\theta_{pol}}{\theta_B^2} \right) \right] \right\} \end{aligned} \tag{B.2}$$

where I have used the fact that

$$\frac{d}{dr}\left\{ \exp\left[-4 \ln(2) \left(\frac{r}{\theta_B} \right)^2 \right] \right\} = -\frac{8 \ln(2) r}{\theta_B^2} \left\{ \exp\left[-4 \ln(2) \left(\frac{r}{\theta_B} \right)^2 \right] \right\} \tag{B.3}$$

$$\sqrt{\theta_{eq}\theta_{pol}} = 2R_p \tag{B.4}$$

$$\tag{B.5}$$

Plugging in some constants into Equation B.2 yields the following

$$\begin{aligned} S_\nu(Jy) &= \frac{2k}{c^2}10^{23}\left[\frac{(2\pi)(10^9)}{(360)(3600)}\right]^2 \frac{\pi\nu^2(GHz)\theta_B^2(arcsec)}{4\ln(2)}\left\{1-\exp\left[-\ln(2)\left(\frac{\theta_{eq}\theta_{pol}}{\theta_B^2}\right)\right]\right\}(T_p-T_{bg})(K) \\ &= 8.179\times 10^{-7}\nu^2(GHz)\theta_B^2(arcsec)\left\{1-\exp\left[-\ln(2)\left(\frac{\theta_{eq}\theta_{pol}}{\theta_B^2}\right)\right]\right\}(T_p-T_{bg})(K) \end{aligned} \tag{B.6}$$

The peak flux densities of the planets are calculated by the `planets` program using Equation B.6.

B.2 Elliptical Gaussian Source

$$\begin{aligned} S_\nu &= \frac{2k}{\lambda^2}\iint_{-\infty}^{\infty}(T_p-T_{bg})\left\{\exp\left[-4\ln(2)\left(\frac{r^2}{\theta_B^2+\theta_{min}^2+\theta_{max}^2}\right)\right]\right\}d^2r \\ &= \frac{2k(T_p-T_{bg})}{\lambda^2}\frac{4\pi}{16\ln(2)}\left[\theta_B^2+\theta_{min}^2+\theta_{max}^2\right] \\ &= \frac{k\pi\theta_B^2(T_p-T_{bg})}{2\ln(2)\lambda^2}\left[1+\frac{\theta_{min}^2+\theta_{max}^2}{\theta_B^2}\right] \end{aligned} \tag{B.7}$$

Plugging in some constants into Equation B.7 yields the following

$$\begin{aligned} S_\nu(Jy) &= \frac{2k}{c^2}10^{23}\left[\frac{(2\pi)(10^9)}{(360)(3600)}\right]^2 \frac{\pi\nu^2(GHz)\theta_B^2(arcsec)}{4\ln(2)}\left\{1+\frac{\theta_{min}^2+\theta_{max}^2}{\theta_B^2}\right\}(T_p-T_{bg})(K) \\ &= 8.179\times 10^{-7}\nu^2(GHz)\theta_B^2(arcsec)\left\{1+\frac{\theta_{min}^2+\theta_{max}^2}{\theta_B^2}\right\}(T_p-T_{bg})(K) \end{aligned} \tag{B.8}$$

Appendix C

Temperature Scales and Telescope Efficiencies

The calibration mode used for essentially all spectral line observations at the 12m is the chopper wheel method (see Ulich & Haas, 1976, ApJS, 30, 247 for a detailed description of this technique). The chopper wheel technique corrects for atmospheric attenuation and several telescope losses. In the following, I describe the temperature scale used at the 12m and how it relates to temperature scales used at other millimeter wavelength observatories.

C.1 Definitions

In the following I define the terms used in the subsequent temperature scale and telescope efficiency discussion. I have tried to adopt a similar nomenclature to that used in Kutner & Ulich (1981, ApJ, 250, 341). Note that throughout this discussion when I refer to a "temperature" I am actually referring to the effective source radiation temperature $J(\nu, T)$, which is defined as:

$$J(\nu, T) \equiv \left(\frac{h\nu}{k}\right) \frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1} \tag{C.1}$$

General Terms

Ω_s	$\equiv$	Solid angle subtended by the source
Ω_d	$\equiv$	Solid angle subtended by the central diffraction beam pattern of the telescope
Ω	$\equiv$	Solid angle on the sky
Ψ	$\equiv$	Direction angle on the sky
P_n	$\equiv$	Normalized antenna power pattern
P_{ng}	$\equiv$	Normalized Gaussian antenna power pattern
B_n	$\equiv$	Normalized source brightness distribution
A	$\equiv$	Airmass toward which the measurement is made

$\tau_0 \equiv$ Atmospheric optical depth at the zenith

$G \equiv$ Maximum antenna gain

Efficiencies

$\eta_r \equiv$ Radiative efficiency

$$\equiv \frac{G}{4\pi} \iint_{4\pi} P_n(\Omega) d\Omega \tag{C.2}$$

$\eta_{rss} \equiv$ Rearward scattering and spillover efficiency

$$\equiv \frac{\iint_{2\pi} P_n(\Omega) d\Omega}{\iint_{4\pi} P_n(\Omega) d\Omega} \tag{C.3}$$

$$\eta_l \equiv \eta_r \eta_{rss} \tag{C.4}$$

$\eta_{fss} \equiv$ Forward scattering and spillover efficiency

$$\equiv \frac{\iint_{\Omega_d} P_n(\Omega) d\Omega}{\iint_{2\pi} P_n(\Omega) d\Omega} \tag{C.5}$$

$\eta_{mb} \equiv$ Main beam efficiency

$$\equiv \frac{\iint_{4\pi} P_{ng}(\Omega) d\Omega}{\iint_{4\pi} P_n(\Omega) d\Omega} \tag{C.6}$$

$\eta_{cmb} \equiv$ Efficiency at which the source couples to the main diffraction beam of the telescope

$$\equiv \frac{\iint_{\Omega_s} P_n(\Psi - \Omega) B_n(\Psi) d\Psi}{\iint_{4\pi} P_{ng}(\Omega) d\Omega} \tag{C.7}$$

$\eta_c \equiv$ Efficiency at which the source couples to the telescope beam

$$\equiv \eta_{cmb} \eta_{mb}$$

$$\equiv \frac{\iint_{\Omega_s} P_n(\Psi - \Omega) B_n(\Psi) d\Psi}{\iint_{4\pi} P_n(\Omega) d\Omega} \tag{C.8}$$

$$\tag{C.9}$$

Temperatures

$T_R \equiv$ Source radiation temperature

$T_A \equiv$ Observed source antenna temperature

$$\equiv \frac{GT_R}{4\pi} \exp(-A\tau_0) \iint_{\Omega_s} P_n(\Psi - \Omega) B_n(\Psi) d\Psi \tag{C.10}$$

$$
\begin{aligned}
T'_A &\equiv \text{Observed source antenna temperature corrected for atmospheric attenuation} \\
&\equiv T_A \exp(A\tau_0) \qquad \text{(C.11)}
\end{aligned}
$$

$$
\begin{aligned}
T^*_A &\equiv \text{Observed source antenna temperature corrected for atmospheric attenuation,} \\
&\quad \text{radiative loss, and rearward scattering and spillover} \\
&\equiv \frac{T'_A}{\eta_r \eta_{rss}} \qquad \text{(C.12)}
\end{aligned}
$$

$$
\begin{aligned}
T^*_R &\equiv \text{Observed source antenna temperature corrected for atmospheric attenuation,} \\
&\quad \text{radiative loss, and rearward and forward scattering and spillover}^1 \\
&\equiv \frac{T^*_A}{\eta_{fss}} \qquad \text{(C.13)}
\end{aligned}
$$

$$
\begin{aligned}
\Delta T_R &\equiv \text{Source radiation temperature excluding any background emission} \\
&\quad \text{(like the cosmic microwave background emission)} \\
&\equiv T_R - T_{bg} \\
&\equiv \frac{T^*_R}{\eta_c} \qquad \text{(C.14)}
\end{aligned}
$$

$$
\begin{aligned}
T_{mb} &\equiv \text{Source brightness temperature as measured by the main diffraction beam} \\
&\quad \text{of the telescope} \\
&\equiv \eta_{cmb} \Delta T_R \qquad \text{(C.15)}
\end{aligned}
$$

C.2 Relations Between Temperature Scales

We can now combine the definitions above to derive the relations between the physical measurements and the temperature scale used at the 12m and the scales used at other telescopes. Combining the equations above, we can relate the source temperature corrected for atmospheric attenuation (T'_A) to many of the antenna and source temperatures:

$$
\begin{aligned}
T'_A &= \eta_r \eta_{rss} \eta_{fss} \eta_c \Delta T_R \qquad \text{(C.16)} \\
&= \eta_l \eta_{fss} T^*_R \qquad \text{(C.17)} \\
&= \eta_l T^*_A \qquad \text{(C.18)} \\
&= \eta_{mb} T_{mb} \qquad \text{(C.19)}
\end{aligned}
$$

[1] T^*_R can also be defined as the source brightness temperature corrected for atmospheric attenuation, radiative loss, and rearward and forward scattering and spillover if the source is equal to or larger than the main diffraction beam.

C.3 Telescope Efficiency Measurements

Telescope efficiencies are normally calculated using a measurement of the continuum brightness of a planet (for η_{mb}) or the Moon (for η_{fss}). In the following I give the relations used to calculate several telescope efficiencies. Since the source coupling between a disk source like the planets and a Gaussian telescope beam is given by:

$$\eta_{cmb} = 1 - \exp\left[-\ln(2)\left(\frac{\theta_s}{\theta_B}\right)^2\right] \tag{C.20}$$

I will use this term in the efficiency equation derivations given below.

C.3.1 Corrected Main Beam Efficiency

The efficiency factor which converts the 12m T_R^* scale to the T_{mb} scale is given by:

$$\begin{aligned} \eta_m^* &= \frac{\eta_{mb}}{\eta_l \eta_{fss}} \\ &= \frac{T_R^*}{T_{mb}} \\ &= \frac{T_R^*}{(T_R - T_{bg})\left\{1 - \exp\left[-\ln(2)\left(\frac{\theta_s}{\theta_B}\right)^2\right]\right\}} \end{aligned} \tag{C.21}$$

One can also calculate η_m^* using the Ruze equation:

$$\eta_m^* = \left[1 + \frac{A_e \theta_e^2}{A_m \theta_m^2}\right]^{-1} \tag{C.22}$$

given that:

$$\theta_e = 2\sqrt{\ln(2)}\frac{\lambda}{\pi c_\sigma} \tag{C.23}$$

$$\theta_m = 1.22\frac{\lambda}{D} \tag{C.24}$$

$$\frac{A_e}{A_m} = \frac{1}{\eta_{a0}}\left[\frac{2c_\sigma}{D}\right]^2\left\{\exp(\delta^2) - 1\right\} \tag{C.25}$$

where λ is the wavelength of observation, c_σ is the correlation scale size of the surface deviations (280 mm), η_{a0} is the zero wavelength aperture efficiency (0.55), and δ is the surface accuracy (75 μm). Figure C.1 shows this relation with the actual measurements given in Table C.1.

C.3.2 Main Beam Efficiency

The efficiency factor which converts any source antenna measurement to the T_{mb} scale is given by:

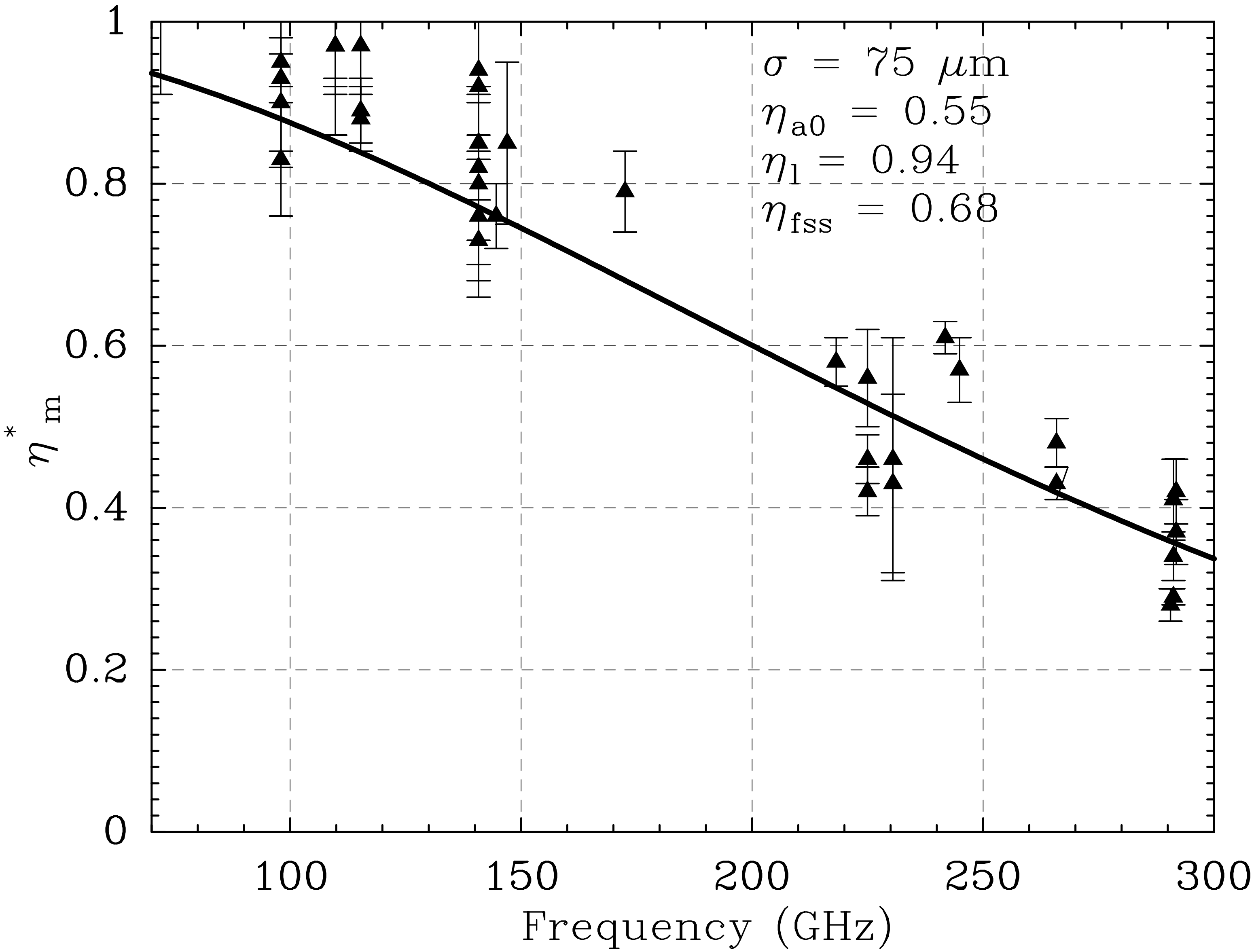

Figure C.1: Measured and theoretical estimates of η_m^* as a function of frequency.

$$\begin{aligned}\eta_{mb} &= \frac{T'_A}{T_{mb}} \\ &= \frac{\eta_l \eta_{fss} T^*_R}{(T_R - T_{bg})\left\{1 - \exp\left[-\ln(2)\left(\frac{\theta_s}{\theta_B}\right)^2\right]\right\}}\end{aligned} \tag{C.26}$$

Table C.1 lists the most recent measurements of η^*_m and η_{mb} for the planets and frequencies given.

Table C.1: 12m Telescope Efficiencies

Frequency (GHz)	Source	Source Size (arcsec)	η^*_m	η_{mb}	Date Measured
72.0	Jupiter	37.4×35.0	1.04±0.13	0.66±0.08	April 1997
98.0	Venus	12.2×12.2	0.90±0.06	0.57±0.04	November 1996
98.0	Mars	8.5×8.4	0.83±0.07	0.53±0.04	June 1997
98.0	Saturn	16.9×15.3	0.93±0.11	0.59±0.07	June 1997
109.8	Venus	22.1×22.1	0.97±0.04	0.62±0.02	August 1996
109.8	Jupiter	43.4×40.6	0.97±0.05	0.62±0.03	August 1996
109.8	Saturn	19.2×17.3	0.97±0.06	0.62±0.04	August 1996
115.3	Jupiter	43.4×40.6	0.88±0.04	0.56±0.02	August 1996
115.3	Saturn	19.2×17.3	0.97±0.06	0.62±0.04	August 1996
140.8	Venus	13.4×13.4	0.73±0.05	0.47±0.03	November 1996
140.8	Mars	5.5×5.5	0.85±0.07	0.54±0.04	November 1996
140.8	Jupiter	35.5×33.2	0.82±0.09	0.52±0.06	November 1996
140.8	Saturn	19.1×17.2	0.92±0.09	0.59±0.06	November 1996
140.8	Uranus	3.5×3.5	0.80±0.10	0.51±0.06	November 1996
140.8	Neptune	2.2×2.2	0.76±0.10	0.48±0.06	November 1996
144.6	Saturn	17.4×15.7	0.76±0.04	0.48±0.03	June 1996
218.2	Saturn	18.0×16.1	0.58±0.03	0.37±0.02	November 1995
230.5	Saturn	19.5×17.6	0.43±0.11	0.27±0.07	October 1996
230.5	Uranus	3.6×3.5	0.46±0.15	0.29±0.09	October 1996
244.9	Mars	7.5×7.5	0.57±0.04	0.36±0.02	December 1996
265.9	Mars	5.5×5.5	0.48±0.03	0.31±0.02	November 1996
291.8	Mars	7.1×7.1	0.42±0.04	0.27±0.02	December 1996
291.8	Saturn	17.8×16.1	0.37±0.04	0.24±0.02	December 1996

Appendix D

Spectral Resolution and Sensitivity Bandwidth in Spectrometers

For many of the spectrometers used at millimeter-wavelength observatories (filter bank spectrometers, correlation spectrometers, *etc.*), the true bandwidth of a single spectrometer channel is a convolution of the original gain response of the channel and any smoothing functions applied. This convolution of the response and smoothing functions affects two important factors:

$\Delta\nu_{FWHP} \equiv$ The full-width to half-power, or -3dB, bandwidth, which is the true "spectral resolution", and

$\Delta\nu_{SB} \equiv$ The "sensitivity bandwidth", which is the channel bandwidth used in calculations of the rms sensitivity in a spectrum.

The sensitivity bandwidth is defined as follows:

$$\Delta\nu_{SB} \equiv \frac{\left[\int_{-\infty}^{\infty} F(\nu)d\nu\right]^2}{\int_{-\infty}^{\infty}[F(\nu)]^2 d\nu} \tag{D.1}$$

Kraus (*Radio Astronomy*, 2nd Edition, page 7-8) defines a similar term.

Table D.1 describes the relationship between $\Delta\nu_{FWHP}$, $\Delta\nu_{SB}$, and the frequency sampling $\Delta\nu$ for various smoothing functions F(ν) assuming Nyquist sampling at $\Delta\nu$. At the end of this Appendix I show the calculation for each of these integrals.

For the filter bank spectrometers at the 12m, the channel response is a second order Chebyshev bandpass filter (which approximates a pill box function), there is no smoothing, and they are **not** Nyquist sampled. A single channel in the Millimeter Autocorrelator (MAC), on the other hand, has a sinc frequency response which is hanning smoothed. Since the convolution of a sinc with any function that is already band-limited within the frequency response of the sinc leaves that function unchanged, we are left with a hanning function response. Therefore:

Table D.1: Spectral Resolution and Sensitivity Bandwidth

F(ν)	$\frac{\Delta\nu_{FWHP}}{\Delta\nu}$ [a]	$\frac{\Delta\nu_{SB}}{\Delta\nu}$ [a]
sinc	1.207	1.000
gaussian	2.000	1.505
hanning	2.000	2.667
hamming	1.820	2.935

[a] $\Delta\nu$ is the frequency sampling interval.

$$
\begin{aligned}
\Delta\nu_{FWHP}^{FB} &= \Delta\nu && \text{(D.2)}\\
\Delta\nu_{FWHP}^{HC} &= 2.000\Delta\nu && \text{(D.3)}\\
\Delta\nu_{SB}^{FB} &= \Delta\nu && \text{(D.4)}\\
\Delta\nu_{SB}^{HC} &= 2.667\Delta\nu && \text{(D.5)}
\end{aligned}
$$

D.1 Function Integrals

D.1.1 Sinc

$$
\begin{aligned}
\Delta\nu_{SB} &= \frac{\left[\int_{-\infty}^{\infty}\frac{\sin\pi\nu}{\pi\nu}d\nu\right]^2}{\int_{-\infty}^{\infty}[\frac{\sin\pi\nu}{\pi\nu}]^2 d\nu} \qquad \text{(D.6)}\\
&= \frac{\left[2\int_{0}^{\infty}\frac{\sin\pi\nu}{\pi\nu}d\nu\right]^2}{2\int_{0}^{\infty}[\frac{\sin\pi\nu}{\pi\nu}]^2 d\nu}\\
&= \frac{\left[\frac{2}{\pi}(\frac{\pi}{2})\right]^2}{\frac{2}{\pi^2}(\frac{\pi^2}{2})}\\
&= 1
\end{aligned}
$$

D.1.2 Gaussian

$$
\begin{aligned}
\Delta\nu_{SB} &= \frac{\left\{\int_{-\infty}^{\infty}\exp(-\ln(2)\nu^2)d\nu\right\}^2}{\int_{-\infty}^{\infty}[\exp(-\ln(2)\nu^2)]^2 d\nu} \qquad \text{(D.7)}\\
&= \frac{\left\{2\int_{0}^{\infty}\exp(-\ln(2)\nu^2)d\nu\right\}^2}{2\int_{0}^{\infty}\left[\exp(-\ln(2)\nu^2)\right]^2 d\nu}\\
&= \frac{\frac{\pi}{\ln(2)}}{\sqrt{\frac{\pi}{2\ln(2)}}}
\end{aligned}
$$

$$
\begin{aligned}
&= \sqrt{\frac{\pi}{2\ln(2)}} \\
&\simeq 1.50538
\end{aligned}
$$

D.1.3 Hanning

The Hanning function is non-zero only from $-(N-1)$ to $N-1$, where N is the number of channels which are being smoothed...

$$\Delta\nu_{SB} = \frac{\left\{\int_{-(N-1)}^{N-1} \frac{1}{2}\Big[1+\cos(2\pi\nu)\Big]d\nu\right\}^2}{\int_{-(N-1)}^{N-1}\left\{\frac{1}{2}\Big[1+\cos(2\pi\nu)\Big]\right\}^2 d\nu} \tag{D.8}$$

Normally, we take 3 channels and give them weights 0.25,0.5,0.25. Therefore, $\Delta\nu_{SB}$ becomes

$$
\begin{aligned}
\Delta\nu_{SB} &= \frac{\left\{\int_{-2}^{2} \frac{1}{2}\Big[1+\cos(2\pi\nu)\Big]d\nu\right\}^2}{\int_{-2}^{2}\left\{\frac{1}{2}\Big[1+\cos(2\pi\nu)\Big]\right\}^2 d\nu} \qquad (D.9) \\
&= \frac{\left\{2\int_{0}^{2} \frac{1}{2}\Big[1+\cos(2\pi\nu)\Big]d\nu\right\}^2}{2\int_{0}^{2}\left\{\frac{1}{2}\Big[1+\cos(2\pi\nu)\Big]\right\}^2 d\nu} \\
&= \frac{4}{\frac{3}{2}} \\
&= \frac{8}{3}
\end{aligned}
$$

D.1.4 Hamming

The Hamming function is just the Hanning function with different weighting.

$$
\begin{aligned}
\Delta\nu_{SB} &= \frac{\left\{\int_{-(N-1)}^{N-1} \Big[0.54+0.46\cos(2\pi\nu)\Big]d\nu\right\}^2}{\int_{-(N-1)}^{N-1}\left\{0.54+0.46\cos(2\pi\nu)\right\}^2 d\nu} \qquad (D.10) \\
&= \frac{\left\{2\int_{0}^{2} \Big[0.54+0.46\cos(2\pi\nu)\Big]d\nu\right\}^2}{2\int_{0}^{2}\left\{0.54+0.46\cos(2\pi\nu)\right\}^2 d\nu}
\end{aligned}
$$

$$
\begin{aligned}
&= \frac{(2.16)^2}{1.5896} \\
&\simeq 2.935078
\end{aligned}
$$

Appendix E

Walsh Function Modulation

All observations which involve position switching or focus modulation (which is usually only done with frequency switching measurements) at the 12 Meter Telescope use a Walsh function cycle for each SIG–REF measurement. For a given measurement of duration P composed of n SIG–REF measurement pairs (a SIG–REF pair is referred to a "repeat" in the 12m telescope lingo), a switching sequence determined by the Walsh function of PALey order $2^n - 1$ is built-up. Building up a PALey order of $2^n - 1$ Walsh functions, where n is the number of ON–OFF pairs, perfectly rejects polynomial drift terms of order up to and including $n-1$. This statement implies that...

$$\int_0^P \left(\sum_1^{n-1} a_{n-1} t^{n-1} \right) PAL(2^n - 1, t) dt = 0 \tag{E.1}$$

This sequence of SIG–REF switching can be truncated at any even point. Ideally it would be trucated after exactly 2^n phases, at which point it gives the maximum rejection of an t^{n-1} and lower order polynomial drift. Although we recommend that observers try to truncate this way, we don't insist on it. The order of polynomial drift completely rejected is then a function of the biggest 2^m sequence (or the inverse of this sequence) that has been repeated without truncation. Since the PALey order is calculated in real time, we don't need to know in advance how many terms there will be. The algorithm is simply the following...

> After every complete set of m (2 or more, but always a power of 2) phases, the next m phases will be a repeat of the first m, with 0 and 1 reversed.

This is equivalent to adding another order of Rademacher function to the R products generating a Walsh function of order $2^n - 1$

$$\begin{aligned} PAL(2^n - 1, t) &= \prod_1^n R(n, t) \\ &= \prod_1^n \left\{ sign \left[\sin(2^n \pi t) \right] \right\} \end{aligned} \tag{E.2}$$

This assures we build up a PALey order of ($2^n - 1$,t), with n being increased by 1 after every complete set, and which means that polynomial drift terms up to order $(n - 1)$ are perfectly rejected.

In practice each phase usually lasts 30 seconds, although phases as short as 10 seconds and as long as a minute are occasionally used. How long a sequence we have really depends on how long the observer wants to integrate. The "0 1 1 0" is normally the shortest sequence, with the 2 pairs of phases. We probably rarely use more than 8 pairs, which would be an 8 minute (in total time) integration at 30 seconds per SIG and REF integration phase. In other words, typical functions are usually PAL(3,T), PAL(7,T) or PAL(15,T). Figure E.1 shows the Walsh functions of order $2^n - 1$ for $n = 1 - 5$.

The following C code fragment (written by Jeff Hagen) is used in the 12 Meter Telescope control program to calculate the Walsh function.

```
walsh(i)
int i;
{
  int bool = 0;
  int mask = 0x8000;

  while(mask) {
    if( mask & i )
      bool += 1;
    mask = mask>>1;
  }
  return( bool % 2 );
}
```

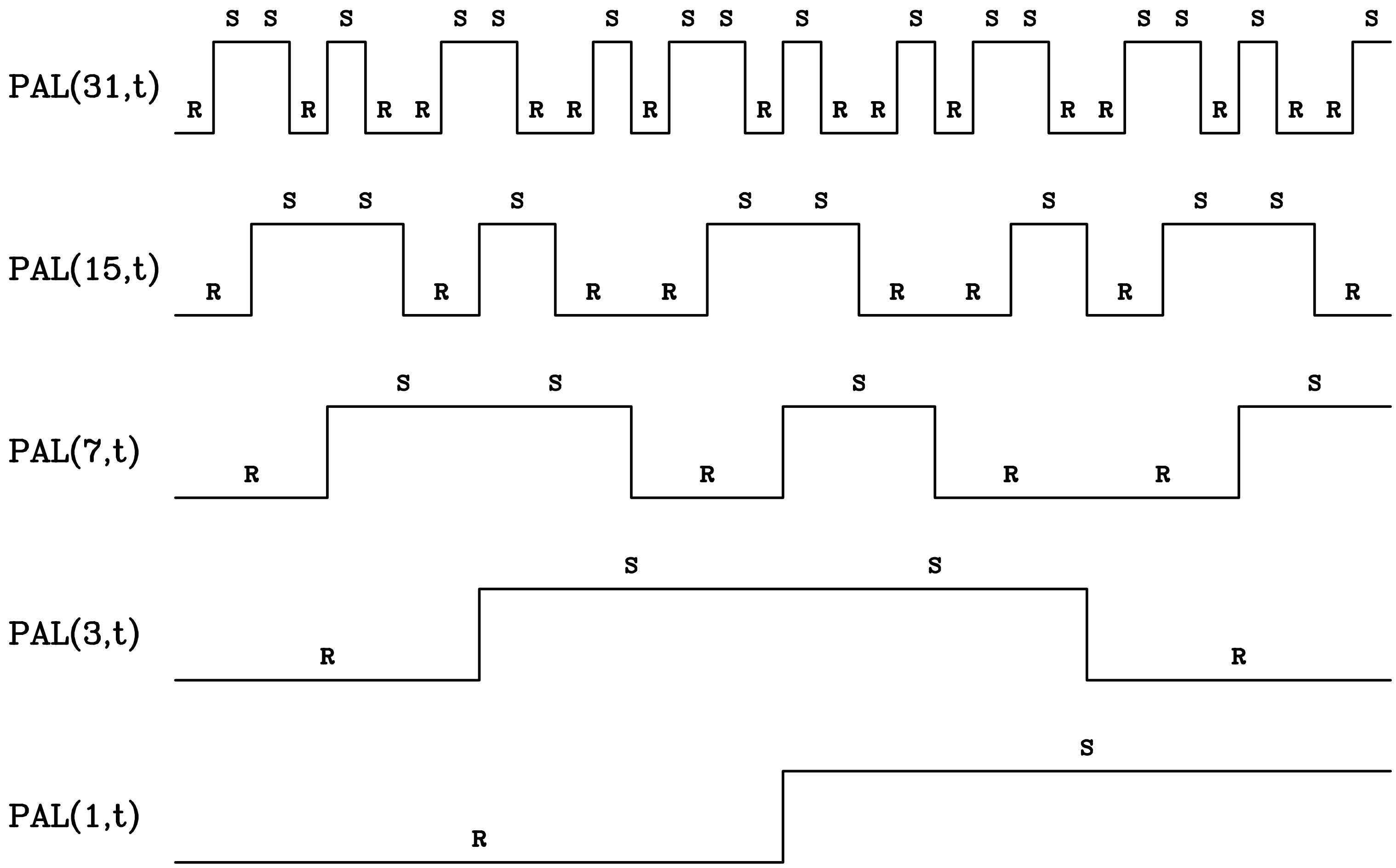

Figure E.1: The first five Walsh functions used in switched observations at the 12 Meter Telescope. The order of the Walsh function PAL is given by $2^n - 1$.

Appendix F

The Radiometer Equation for Position Switched Measurements

Defining the following

$$
\begin{aligned}
T_{rms}^{pos} &\equiv \text{rms noise level for an ON, OFF or GAIN scan measurment} \\
&\equiv \frac{T_{sys}}{\eta_{spec}\sqrt{\Delta\nu t_{pos}}} && \text{(F.1)} \\
\mathsf{SCAN} &\equiv \frac{\mathsf{ON}-\mathsf{OFF}}{\mathsf{OFF}} \times \mathsf{GAIN} && \text{(F.2)} \\
\alpha &\equiv \frac{t_{off}}{t_{on}} && \text{(F.3)} \\
\eta_{spec} &\equiv \text{spectrometer efficiency (see Table F.1)} && \text{(F.4)} \\
& && \text{(F.5)}
\end{aligned}
$$

we can calculate $(T_{rms}^{scan})^2$

$$
\begin{aligned}
(T_{rms}^{scan})^2 &= \left(\frac{\mathsf{ON}-\mathsf{OFF}}{\mathsf{OFF}} \times \mathsf{GAIN}\right)^2 \left\{ \frac{(T_{rms}^{on})^2 + (T_{rms}^{off})^2}{\left(\mathsf{ON}-\mathsf{OFF}\right)^2} + \frac{(T_{rms}^{off})^2}{\mathsf{OFF}^2} + \frac{(T_{rms}^{gain})^2}{\mathsf{GAIN}^2} \right\} \\
&= \left(\frac{\mathsf{GAIN}}{\mathsf{OFF}}\right)^2 \left((T_{rms}^{on})^2 + (T_{rms}^{off})^2\right) && \text{(F.6)}
\end{aligned}
$$

where I have neglected terms quadratic in $\frac{\mathsf{ON}-\mathsf{OFF}}{\mathsf{OFF}}$. Noting that

$$(T_{rms}^{on-off})^2 = (T_{rms}^{on})^2 + (T_{rms}^{off})^2 \qquad \text{(F.7)}$$

we see that Equation F.7 and Equation F.6 differ by only a constant (which is the volt-to-temperature scaling factor). Therefore

$$
\begin{aligned}
T_{rms}^{scan} &= \frac{T_{sys}}{\eta_{spec}\sqrt{\Delta\nu}}\left[\frac{1}{t_{on}} + \frac{1}{t_{off}}\right]^{\frac{1}{2}} \\
&= \frac{T_{sys}}{\eta_{spec}\sqrt{\Delta\nu}}\left[\frac{1}{t_{on}} + \frac{1}{\alpha t_{on}}\right]^{\frac{1}{2}} \\
&= \frac{T_{sys}}{\eta_{spec}\sqrt{\Delta\nu t_{on}}}\left[1 + \frac{1}{\alpha}\right]^{\frac{1}{2}} \qquad \text{(F.8)}
\end{aligned}
$$

If one is taking multiple ON scans per OFF scan, then the time spent to acquire a scan is given by

$$
\begin{aligned}
t_{scan} &= t_{on} + \frac{t_{off}}{N} \\
&= \left(1 + \frac{\alpha}{N}\right)t_{on} \qquad \text{(F.9)}
\end{aligned}
$$

where N is the number of ON source measurements per OFF source measurement. Therefore, T_{rms}^{scan} becomes

$$
\begin{aligned}
T_{rms}^{scan} &= \frac{T_{sys}}{\eta_{spec}\sqrt{\Delta\nu\left(\frac{t_{scan}}{1+\frac{\alpha}{N}}\right)}}\left(1 + \frac{1}{\alpha}\right)^{\frac{1}{2}} \\
&= \frac{T_{sys}}{\eta_{spec}\sqrt{\Delta\nu t_{scan}}}\left[\left(1 + \frac{\alpha}{N}\right)\left(1 + \frac{1}{\alpha}\right)\right]^{\frac{1}{2}} \qquad \text{(F.10)}
\end{aligned}
$$

To determine the optimum OFF source integration time time when one is acquiring multiple ON source measurements per OFF source measurement, we find the minimum of Equation F.10 with respect to α:

$$
\begin{aligned}
\frac{dT_{rms}^{scan}}{d\alpha} &= \frac{T_{sys}}{\eta_{spec}\sqrt{\Delta\nu t_{scan}}}\left\{\frac{1}{2N}\left(1 + \frac{\alpha}{N}\right)^{-\frac{1}{2}}\left(1 + \frac{1}{\alpha}\right)^{\frac{1}{2}} - \frac{1}{2\alpha^2}\left(1 + \frac{\alpha}{N}\right)^{\frac{1}{2}}\left(1 + \frac{1}{\alpha}\right)^{-\frac{1}{2}}\right\} \\
&= 0 \qquad \text{(F.11)}
\end{aligned}
$$

which reduces to

$$
\begin{aligned}
\left(\frac{1}{N}\right)\left(\frac{N}{N+\alpha}\right)^{\frac{1}{2}}\left(1 + \frac{1}{\alpha}\right)^{\frac{1}{2}} &= \left(\frac{1}{\alpha^2}\right)\left(\frac{N+\alpha}{N}\right)^{\frac{1}{2}}\left(\frac{\alpha}{1+\alpha}\right)^{\frac{1}{2}} \\
\alpha^2 &= N \\
t_{off}^{optimal} &= \sqrt{N}t_{on} \qquad \text{(F.12)}
\end{aligned}
$$

Table F.1: 2-Bit Correlator Efficiencies

Number of Levels	η_{spec}[1]	TMS Equation and Page
2	$\frac{2}{\pi}$	8.31, page 220
3	0.809	8.58, page 228
4	0.881	8.50, page 224
5	0.920	...
8	0.962	...

where I have used Equation F.3. Inserting this value for $t_{off}^{optimal}$ into Equation F.10 leads to the following relation for the optimal scan rms when one observes N ON source measurements per OFF source measurement

$$^{optimal}T_{rms}^{scan} = \frac{T_{sys}}{\eta_{spec}\sqrt{\Delta\nu t_{scan}}}\left(1 + \frac{1}{\sqrt{N}}\right) \tag{F.13}$$

See Ball (1976, "Methods of Experimental Physics", volume 12, part C, page 52) for a parallel discussion on noise considerations for position switched measurements.

The factor η_{spec} takes account of the efficiency for quantized correlation spectrometers like the 12m MAC. Cooper (1976, "Methods of Experimental Physics", volume 12, part B, page 284) discusses this correlator efficiency and quotes the η_{spec} values noted in Table F.1.

Note that the quoted values assume Nyquist sampling. Many correlators, including the MAC, oversample by some amount, so the correlator efficiency is actually somewhat higher than that for Nyquist sampled data. The theoretical calculations are always predicated on having rectangular passbands of exactly the nominal bandwidth, whereas the effective bandwidth with practical filters is always smaller. This and the fact that there are various non-ideal properties of digitizers will tend to reduce the efficiency. Thus, for the purpose of estimating the required observing time to reach a given sensitivity, users should use the theoretical efficiency for Nyquist sampling since the benefit of oversampling will be cancelled by miscellaneous other losses. Formulas for calculating the correlator efficiency for arbitrary oversampling factors can be found in Thompson, Moran, and Swenson (1986) and are listed in Table F.1. For the MAC, which is a 2-bit, 3-level correlator, the correlator efficiency is plotted in Figure F.1.

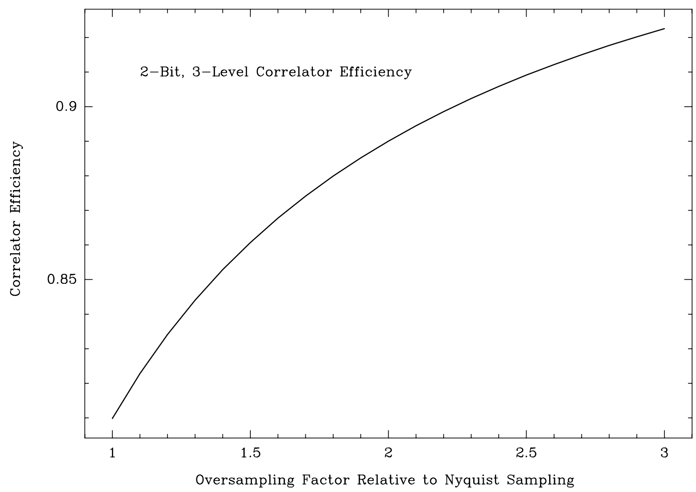

Figure F.1: Correlator efficiency for the MAC (a 2-bit, 3-level correlator) as a function of oversampling. Note that for the MAC, which is oversampled by a factor of $\frac{4}{3}$ over Nyquist, the efficiency is 0.847.

Appendix G

The 12m Telescope Primary Focus Plate Scale

The primary focus plate scale, which determines the amount of beam displacement as a function of lateral displacement of the subreflector, is given by

$$\sin(\theta) = \frac{\Delta x}{f} \left\{ \frac{\frac{\int_0^1 F(r) r^3 dr}{1+\left(\frac{r}{2f}\right)^2}}{\int_0^1 F(r) r^3 dr} \right\} \tag{G.1}$$

where θ is the beam deviation on the sky, F(r) is the receiver feed illumination pattern, and f is the primary focal length. The term in braces is often called the "beam deviation factor". For the 12m receivers F(r) is given by

$$F(r) = \exp(-2.57 \tan^{-1}(0.5952r)) \tag{G.2}$$

For the 12 Meter Telescope, f = 0.42×D, which means that the beam deviation factor is 0.827 and that

$$\boxed{\text{the plate scale for prime focus subreflector lateral movement} = 31.5\ ''/\text{mm}}$$

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