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 ±4.5′ (a throw larger than ±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
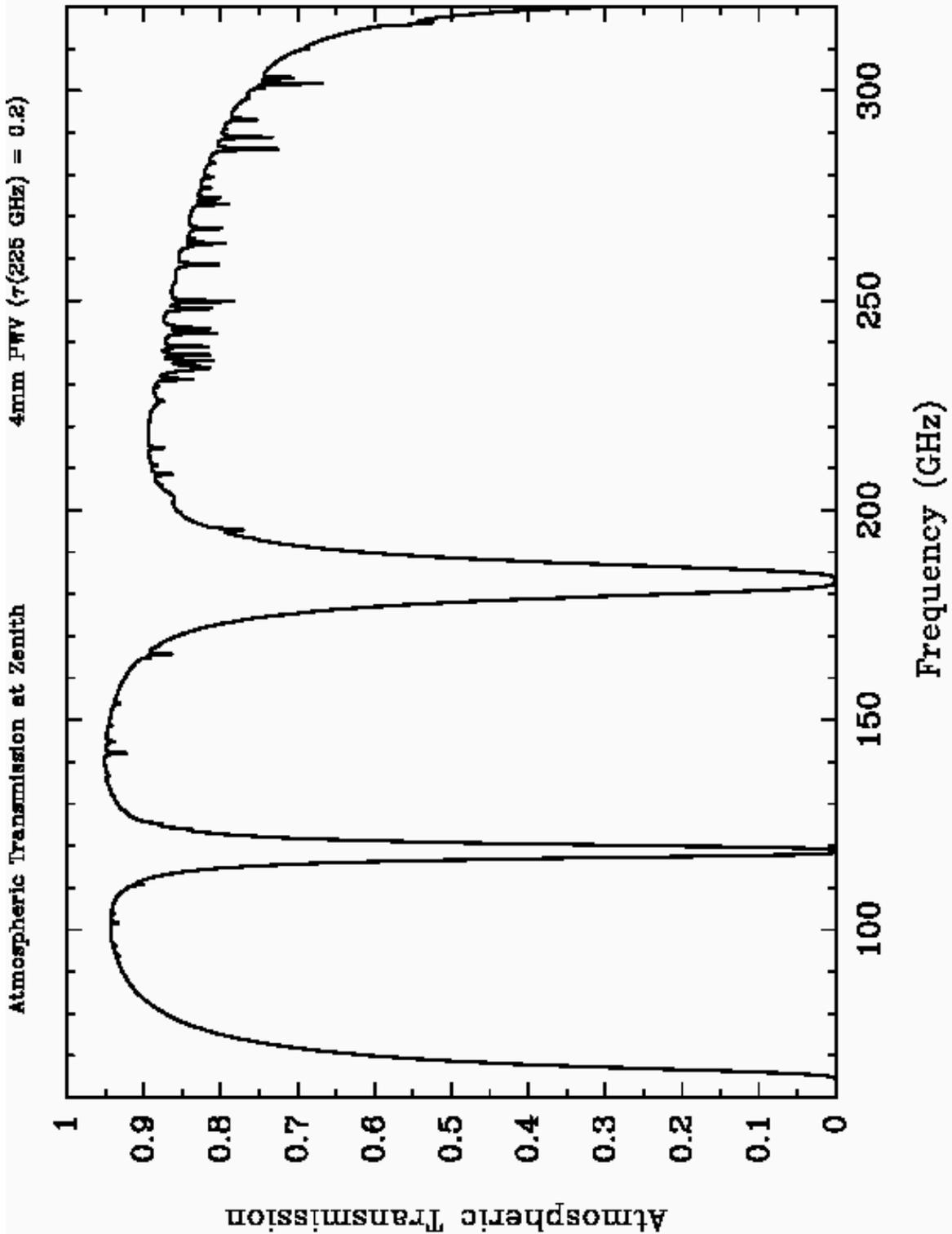
Figure 6.1: Atmospheric transmission as a function of frequency. The range in frequency shown covers that accessible with the 12m receivers. Typical atmospheric conditions with an atmospheric water content of 4mm precipitable water vapor have been used in these calculations.

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 (« 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

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

where

k is Boltzmann's constant (1.380662 x 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

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

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

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

Table 6.1: 12m Receiver Continuum Sensitivities

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:

$\Phi_1 = SIG + CAL$

$\Phi_2 = REF + CAL$

$\Phi_3 = SIG$

$\Phi_4 = REF$

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

$$
\begin{bmatrix} S_1, \Phi_1 \\ S_1, \Phi_2 \\ S_1, \Phi_3 \\ S_1, \Phi_4 \end{bmatrix}
\begin{bmatrix} S_2, \Phi_1 \\ S_2, \Phi_2 \\ S_3, \Phi_3 \\ S_4, \Phi_4 \end{bmatrix}
\begin{bmatrix} S_3, \Phi_1 \\ S_3, \Phi_2 \\ S_3, \Phi_3 \\ S_3, \Phi_4 \end{bmatrix}
\begin{bmatrix} \cdots \\ \cdots \\ \cdots \\ \cdots \end{bmatrix}
$$

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

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

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

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

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:

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:

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

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

$$F_{vane} \quad = \quad \left(\frac{T_c}{VANE - SKY} \right) \exp\left(A \tau_0 \right) \qquad\qquad (6.4)$$

$$F_{fixed} \quad = \quad \left(\frac{T_c}{10^4} \right) \exp\left(A \tau_0 \right)$$

$$F_{noisetube} \quad = \quad \left(\frac{T_c}{C} \right) \exp\left(A \tau_0 \right)$$

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

$$tsys \quad = \quad \left(\frac{\Phi_4}{\Phi_2 - \Phi_4} \right) T_c$$

$$= \quad \frac{REF}{(REF + CAL) - REF} \; T_c \qquad\qquad (6.7)$$

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

$$tpsn \ = \ 0.5 \times \frac{\Phi_1 - \Phi_2 + \Phi_3 - \Phi_4}{\Phi_3 + \Phi_4}$$

$$= \ \frac{SIG - REF}{SIG + REF}$$

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 **ON**s, **OFF**s, 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
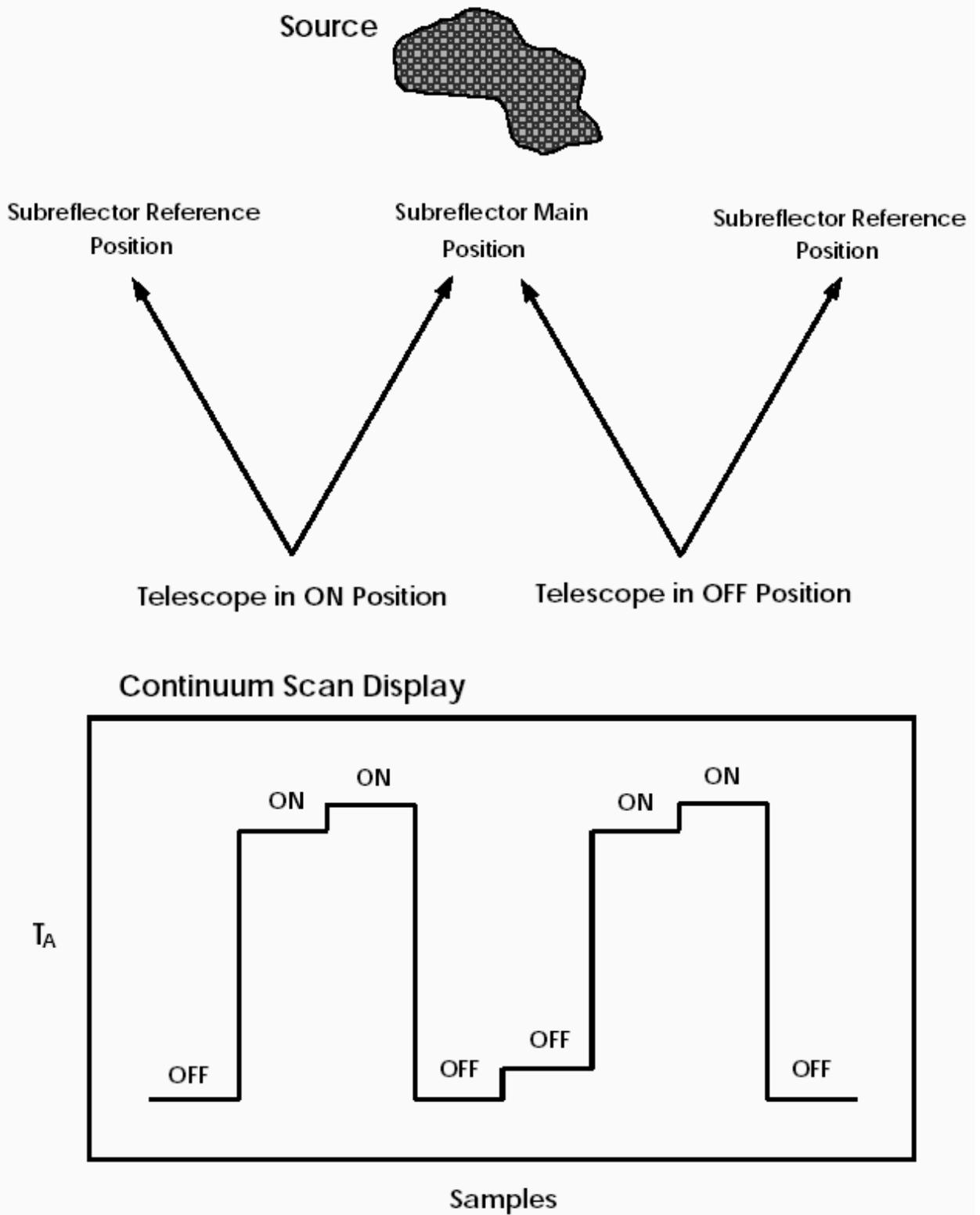
Figure 6.2: Position definitions for continuum sequences.

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 x6.3.5.

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

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

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

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

(6.10)

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

Table 6.2: Sky Tip Antenna Positions

where v 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(v,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

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

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:
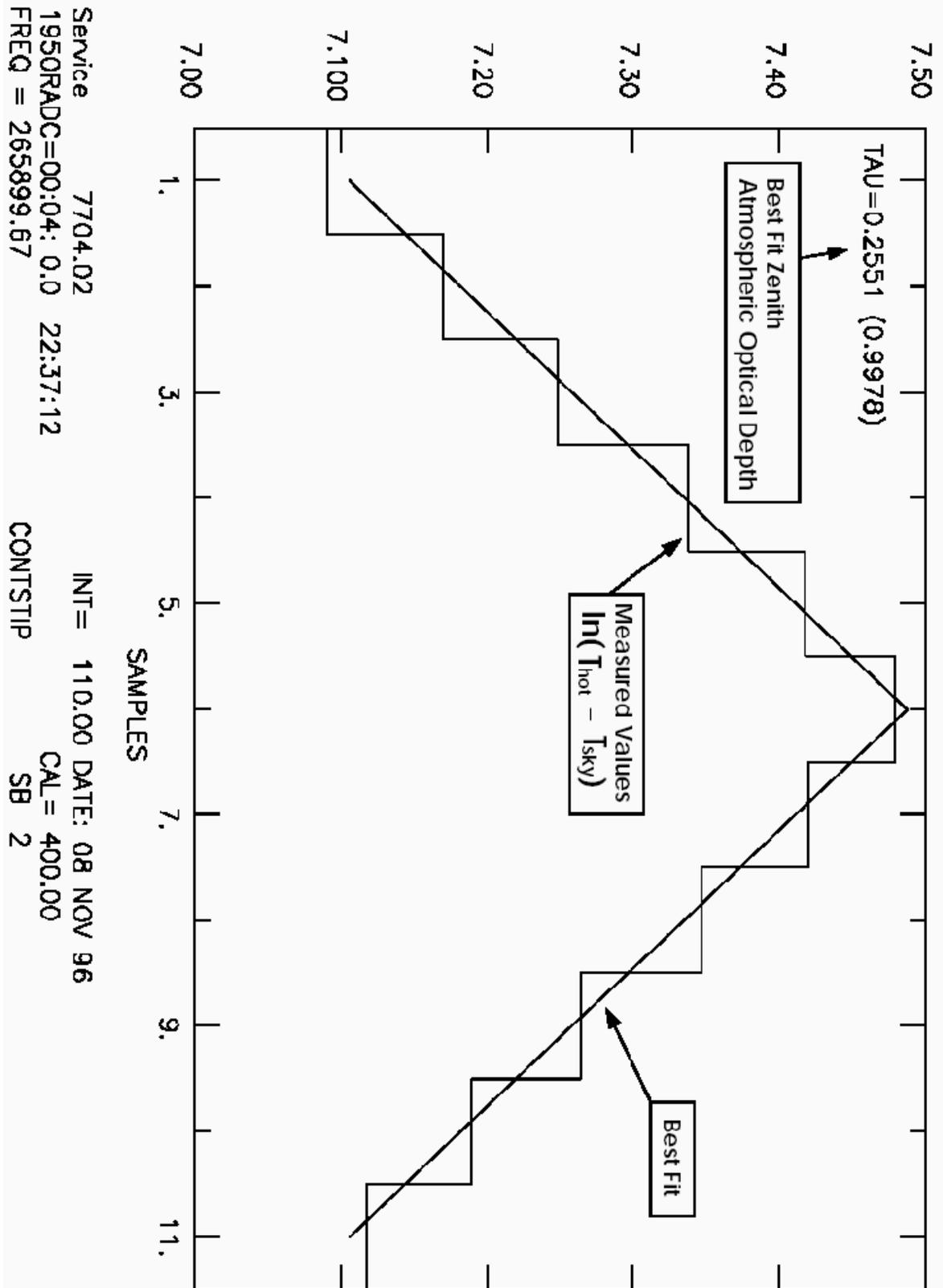
Figure 6.3: Sample SPTIP tipping scan.

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 $\dfrac{T_m}{T_{amb}}$ (called *ftm* in *condar*) and

$\dfrac{T_{spill}}{T_{amb}}$ (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 **CALIBRATE**s may be necessary. The operator can command the system to perform
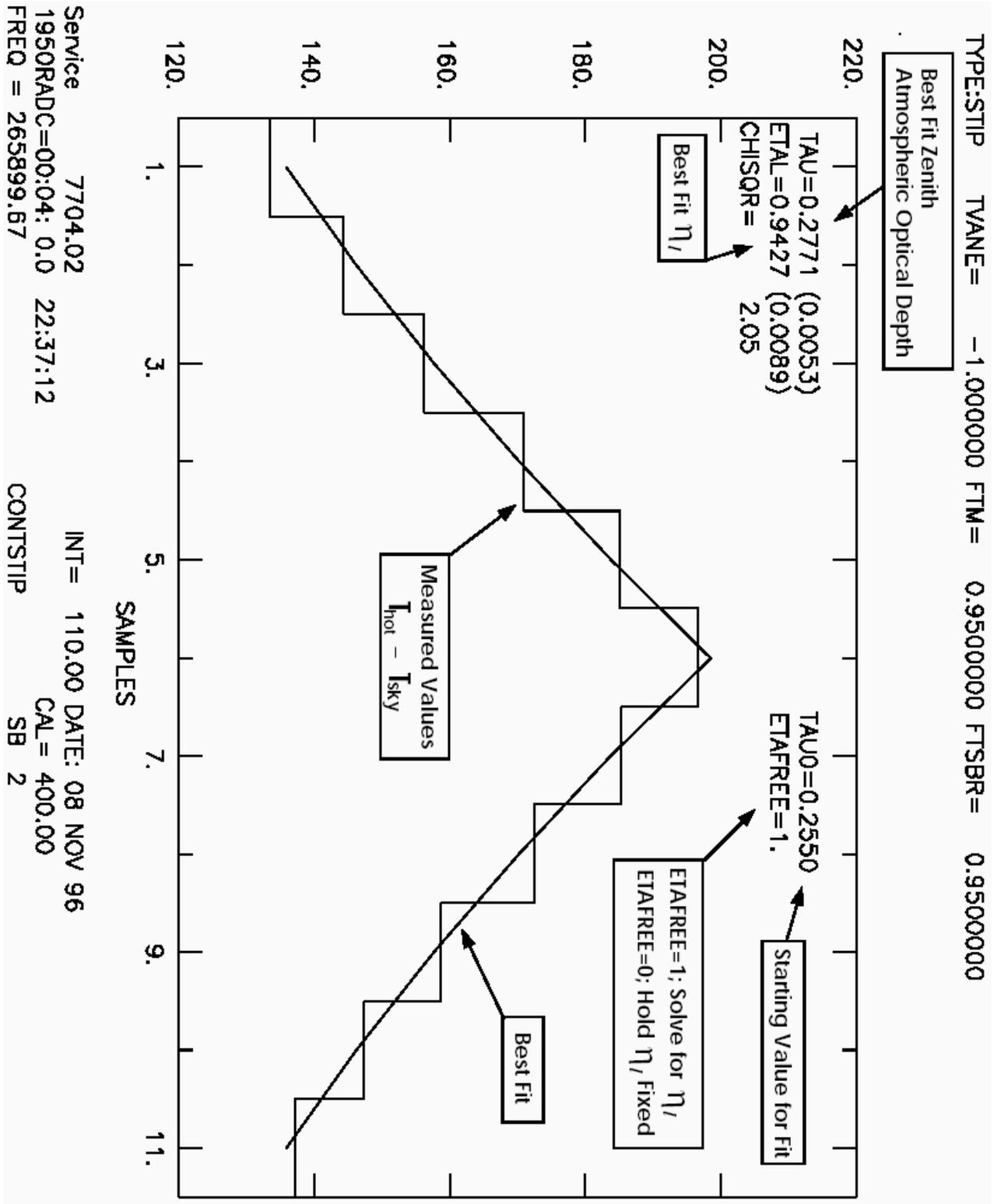
Figure 6.4: Sample STIP tipping scan.

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 Tc 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

$$Y = \frac{V_{hot}}{V_{cold}} \qquad (6.15)$$

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.

Planet	Tb(90 GHz) (K)	TB(150 GHz) (K)	Unit Semi-Diameter (arcsec)
Venus	367±10	294±22	8.34
Mars	207±6	210±10	4.68
Jupiter	172±1	173±1	95.20
Saturn	149±4	137±11	78.15
Uranus	135±4	112±5	35.02
Neptue	130±5	107±5	33.50

Table 6.3: Planetary Flux Density Standards

6.6.2 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.

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

Table 6.4: Flux Density Calibrators

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: Azimuth 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
   RNAME
   7705  Mars    6:57      8:49:53    13:04:21  -0.011  08 Nov  sys  VLG
                                                                289

2             R.A.         DEC.
   TOTAL      10:30:06.5   11:15:35.7
   B1950.0    0:00:00.0    0:00:00.0
   APPARENT   10:30:06.5   11:15:35.7
   GALACTIC   133.94746    1.06432
   OFFSET     0:00:00.0    0:00:00.0

3            APEX
   NS   +0.500
   EW   +0.515
        +0.000

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

6   POINT      0:00:14.3    -0:00:20.5
    PSREF      0:00:00.0    0:00:00.0
    +BEAM   1:00   0:00   QX  -6.36     FREQUENCY
    -BEAM  -1:00   0:00   QY  +5.20     265.886432
                                        265.886432
                                        1956.293860
                                        1956.293860

5   ATM   RCVR   RBAY  FO    TC      TAU0    FWHM  TSYS
    1.17  1mmhi  4     43.3  400.0   0.223   0:30  69C
    MM H2O-> 2.54            400.0   0.127   0:15  67C

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

8          TOL   FOCUS  TORR   %RH  T_AMB   REFRT  MODE  SCANS  SAMPLES  SEC   TIME
   INPUT   0:05  45.7   513    3    13.4    46.2   QK5   4      40       7.0   4:40
   ACTUAL  0:00  45.6   WIND-> 114 @ 21     46.2                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