

Radio Astronomy in the Undergraduate Classroom

Chautauqua
NSF Short Course for College Teachers



User guide:

Haystack 37-meter Radio Telescope
The Small Radio Telescope (SRT)

Harvard University and NEROC Haystack Observatory

May 24-26, 2005

Getting Started

Input commands listed below are color-coded

Red indicates commands entered into the *Umbrella* telescope control program

Green indicates entries into **any** xterm window

Blue indicates entries made to the CLASS data reduction program

37-meter Telescope Control Room

1. Login to the control computer labeled **Fourier**:

username: **chautauqua**

password: *********

2. At the opening of the LINUX window, click on the xterm box (lower right of the window) once.

3. Move the xterm window to the lower left of the screen and at the prompt, type;

chautauqua@fourier% **US**

Your Computer screen configuration will look similar to this:

Remote Computer

For MS-Windows, activate an X-Windows emulation program such as eXceed, or X-Win32.

You will also need to have a Secure Shell login to the Fourier control computer. A freeware program called PuTTY can be downloaded from:

www.chiark.greenend.org.uk/~sgtatham/putty/download.html

SSH to: *fourier.haystack.mit.edu* using the following steps

Open the PuTTY control panel window by clicking on **putty.exe**.

You should see a window like the one below. Take the following actions

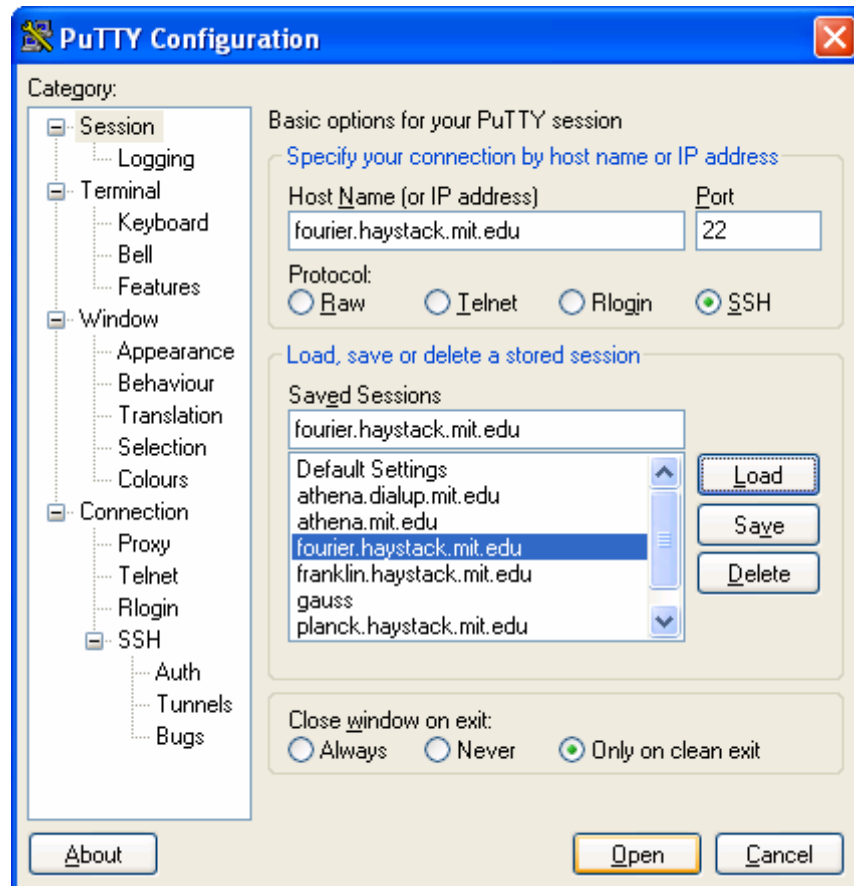
Select SSH on the Protocol bullet

Type: *fourier.haystack.mit.edu* **in the Host Name window.**

Type: *fourier.haystack.mit.edu* **in the Saved Sessions window.**

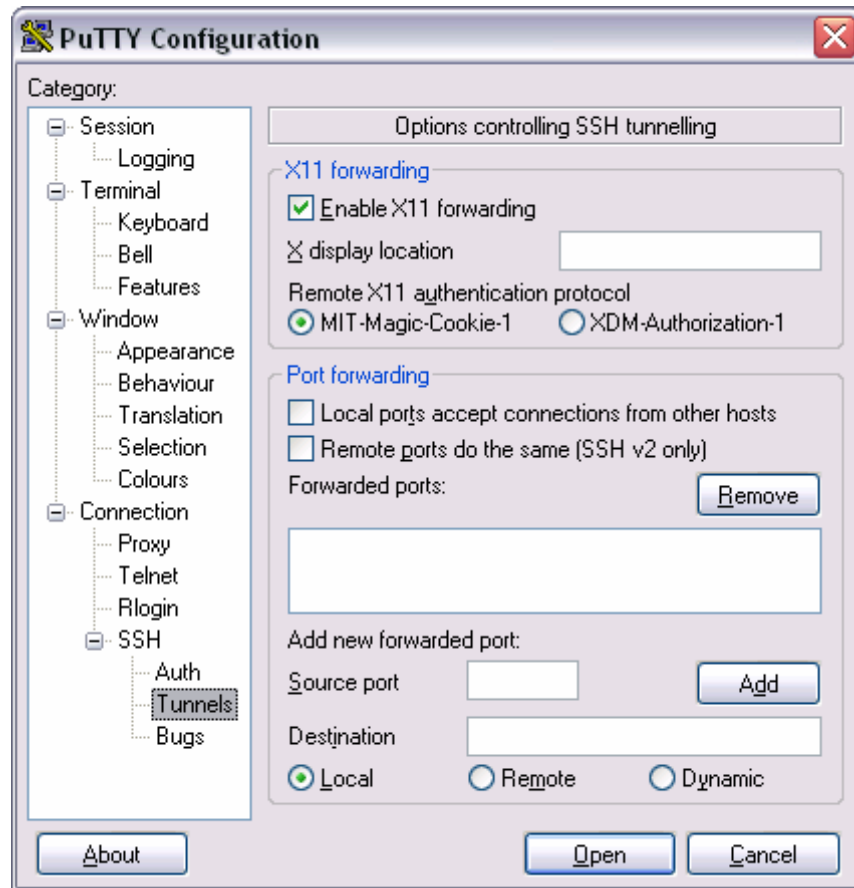
Click Save

Then click the word “Tunnels” on the left-hand column. A window will open entitled “Options controlling SSH tunneling”



Check the box near the top labeled “Enable X11 forwarding”

Click Open



A window will open to allow you to enter your user name and password

Login to the control computer:

username: **chautauqua**
password: *********

At the prompt, type:

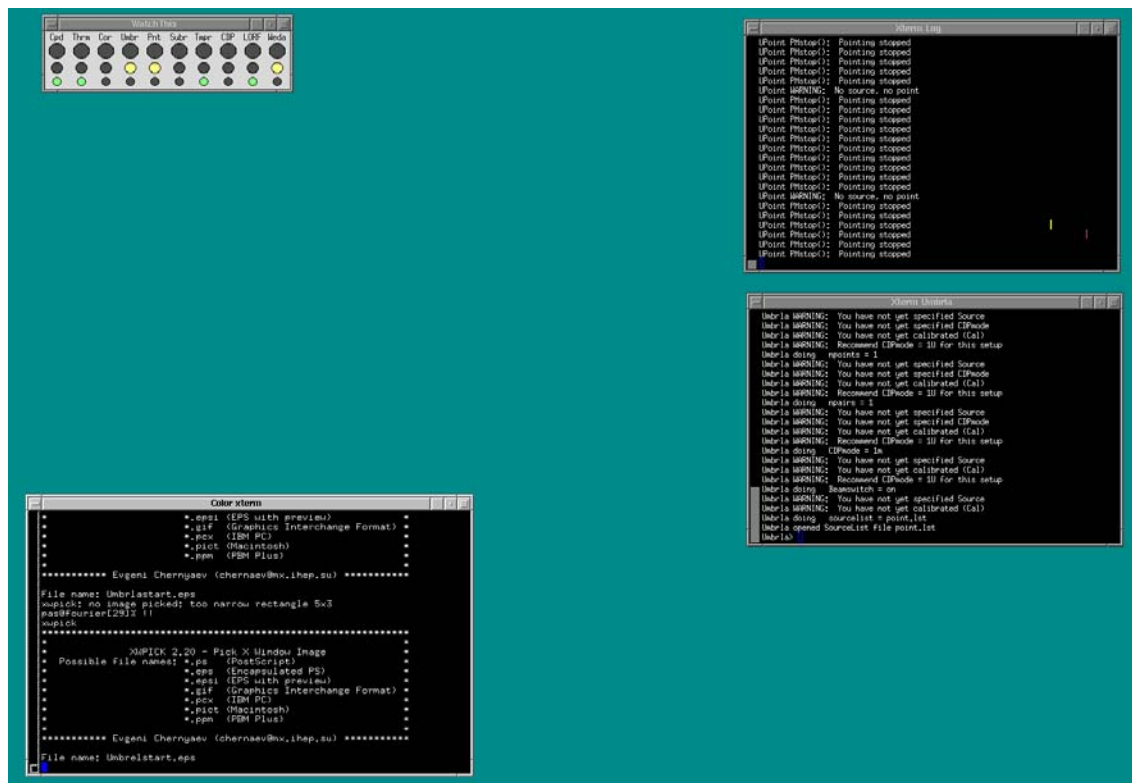
chautauqua@fourier% **Xterm**

When the white Fourier xterm window opens, you may (if you wish) exit the black SSH login window

Move the xterm window to the lower left of the screen and at the prompt, type;

chautauqua@fourier% **US**

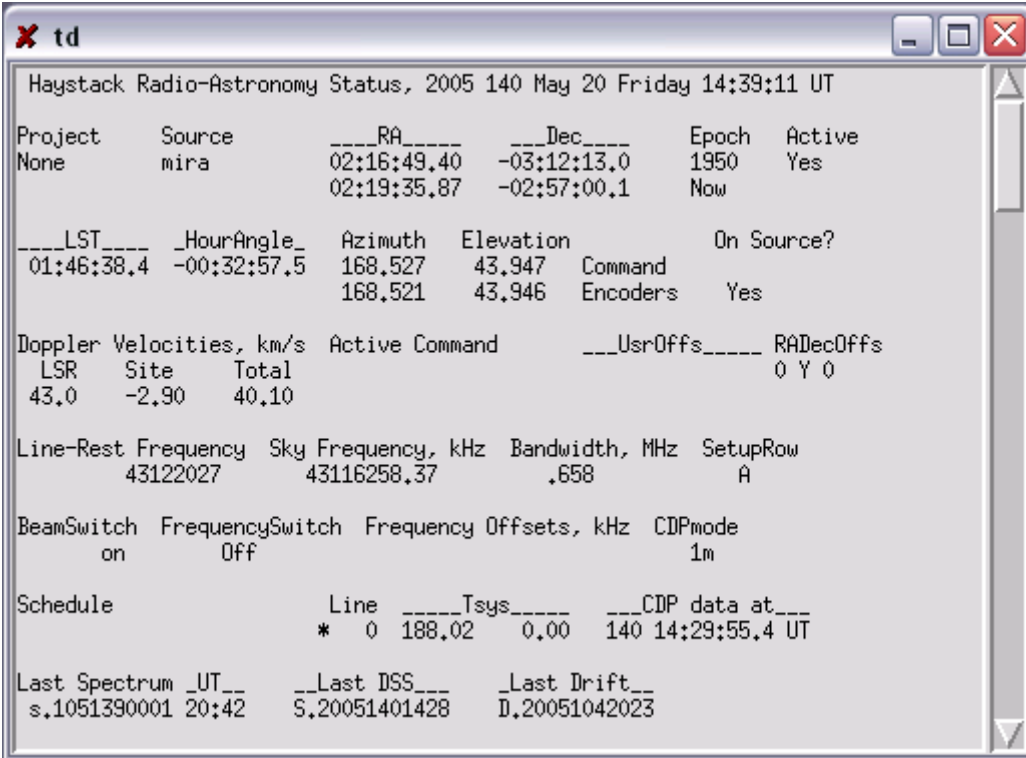
The "US" command will open two xterm windows and a WatchThis "stop light" display. **WatchThis** is a point-and-click sub-systems monitor. The lower right xterm window is the active command input window for the antenna control software called "**Umbrella**". All red typed input commands are entered here.



The screen shown above is from the main console window in the Haystack control room. The "US" command was entered at a system prompt on the **Color Xterm** at the lower left. The two right-hand windows and the **WatchThis** monitor open in the places depicted here. This is why it is prudent to move the **Color Xterm** window to the location shown **BEFORE** opening the Umbrella program. The windows will open in the approximate positions shown if you are using a remote LINUX or MSWindows system.

WatchThis

Move your mouse pointer to the “WatchThis” window and click on one of the lights below the **Umbr** label. This will open the Umbrella monitor window (Haystack Radio-Astronomy Status). The window is labeled “**td**” simply because it is the fourth label from the left on the WatchThis window. (Please excuse the left-to-right reading bias). An example of the monitor window can be seen below. It is **HIGHLY** recommended that the user keep this window open for reference during an observing run. Contained therein is all the basic information needed to see what is going on at any particular time.



```
Haystack Radio-Astronomy Status, 2005 140 May 20 Friday 14:39:11 UT
Project      Source      ___RA_____  ___Dec_____  Epoch  Active
None         mira        02:16:49.40  -03:12:13.0   1950   Yes
             02:19:35.87  -02:57:00.1   Now
___LST_____  _HourAngle_  Azimuth  Elevation  On Source?
01:46:38.4   -00:32:57.5  168.527   43.947   Command
             168.521     43.946   Encoders   Yes

Doppler Velocities, km/s  Active Command  ___UsrOffs_____  RADecOffs
LSR  Site  Total  0 Y 0
43.0  -2.90  40.10

Line-Rest Frequency  Sky Frequency, kHz  Bandwidth, MHz  SetupRow
43122027            43116258.37        .658            A

BeamSwitch  FrequencySwitch  Frequency Offsets, kHz  CDPmode
on          Off              1m                      1m

Schedule
Line  ___Tsys_____  ___CDP data at___
* 0  188.02     0.00     140 14:29:55.4 UT

Last Spectrum _UT__  ___Last DSS___  ___Last Drift___
s.1051390001  20:42          S.20051401428   D.20051042023
```

The **td** window lists the user selected Project name the current source and position (coordinate epoch as well as current precessed position), the current Local Sidereal Time, the Universal Time UT (Greenwich Mean Time), the currently selected observing frequency as well as the actual frequency on the sky (Line-Rest frequency adjusted for source Doppler velocity), listing of observing bandwidth, and observing mode (whether or not any beam or frequency switching is in use), the current system temperature (see, section 1.) and the file names of the last spectrum, discrete-source-scan and drift-scan.

Basic Radiometer Setup

Before you can use the 37-meter telescope to observe your favorite quasar, planet or molecule, you will need to set some initial parameters and system flags. The user needs to select an observing frequency, and observing bandwidth and you need to have some idea of an appropriate integration time for the source you have chosen. This section will list some of the possible settings and give some short explanation of “Why do they do that?”

The basic setup parameters necessary to make a successful observation are listed below. These are discrete commands entered into the **Umbrella** telescope control program. A manual of Umbrella commands can be found at <http://web.haystack.mit.edu/37m/umbrella.html>

```
Umbra> Project =  
Umbra> Maintenance =  
Umbra> Frequency =  
Umbra> CDPMode =  
Umbra> SetupRow =  
Umbra> Bandwidth =  
Umbra> IntTime =  
Umbra> Sourcelist =
```

NOTE: The participants at this Chautauqua class have a sub-directory (/home/chautauqua) set aside on the telescope control computer known as **fourier.haystack.mit.edu**. When we list a **sourcelist** name or other specific file, the file will already be resident in the Chautauqua sub-directory.

```
Umbra> Project =
```

Typically you would use the proposal name assigned by the observatory. This will assist the staff in tracking and retrieving your spectra or continuum data from archives and in the clearing of disk space.

```
Umbra> Maintenance =
```

This command sets important data taking flags in the Pointing Computer (Fourier). The Maintenance= command should be inserted **before** the Frequency= command. Maintenance= resets the beamswitch status to *off* as part of the maintenance on/off checks.

```
Umbra> Frequency =
```

Enter a microwave frequency in **kHz** in the following ranges: 18000000 – 25000000 or 35000000 – 50000000 (**example:** for continuum observations, any frequency will work. For spectral line observations, SiO(1,1) = 43122027)

Umbra> **CDPMode =**

The CDP (Continuum Data Processor) processes total power data depending on the mode selection and observing parameters. Possible selections:

- 1M – 1 channel, modulated calibration (used with beamswitching)
- 2M – 2 channel, modulated
- 1U – 1 channel un-modulated (typically used with frequency switching)
- 2U – 2 channel un-modulated

Umbra> **SetupRow = A or C**

This command tells the correlator how many video converters you wish to use for your observations. This runs the same setup program that is initiated by the Bandwidth= command and allows the user the flexibility to use one or more video converters without changing the previously set switching parameters. This can be useful when switching between pointing and spectroscopy.

- A = One receiver channel
- C = Two receiver channels

Umbra> **Bandwidth = nnn**

This command sends the observing bandwidth selection to the video-converters. The default selections for Dicke switching rate and percent blanking are set. Available choices:

nnn = 160, 53.3, 17.8, 5.93, 1.98 or 0.658 MHz

Umbra> **IntTime = n**

The time desired to complete an observation. IntTime is interpreted differently depending on whether you are observing a continuum or spectral-line source.

- For **continuum**, the integer selection, $n = n$ seconds of observing time
- For **spectral-line**, the integer selection, $n = n \times 30$ seconds of observing time

Umbra> **Sourcelist = *yourfile.lst***

The SourceList= command allows the user to open any sourcelist either already on the control computer or a list the user wishes to create from their program sources. Planets do not require the use of a SourceList= command since the solar/lunar and planetary ephemeris is resident on the computer. Other galactic or extra-galactic sources must be included in an ASCII sourcelist readable by the Umbrella program. **We ask that user sourcelist names end with the .lst suffix.** The list must include: SourceName, Right Ascension, Declination, Epoch, VLSR

In the form: **Name hh mm ss.s dd mm ss yyyy Vel**

With the Umbrella Program opened, and the basic radiometer setup parameters in place, the user will need to perform some basic system tests and calibrations before beginning a spectral-line or continuum observing run.

The user should:

- 1. Measure the System Temperature**
- 2. Measure any pointing offsets**
- 3. Perform a focus measurement**

This handbook will allow you to step through these procedures and read a short explanation of how to interpret your results. While there are several errors that could occur to invalidate your calibration checks, it is hoped that the explanations given will guide enough to know when you have a good measurement.

Following the calibration, pointing and focus checks, a short set of instructions are provided to show you basic observations setups used by student conducting undergraduate research or observations for a typical astronomy lab exercise.

A longer section follows that will describe a lab exercise that has been used by students visiting Haystack from Boston University. Included in the BU lab section is a short tutorial on the use of **Class** which is part of the “**Grenoble Image and Line Data Analysis Software**” available from The [Iram Group](http://www.iram.fr) in Grenoble, France. (www.iram.fr)

1. Measure of the System Temperature.

This is not a physical temperature but rather a measure of the noise contributions from receiver components, waveguide, cables and noise received at the feed-horn from the sky and other sources outside of the radiometer system. When the telescope receives radiation, the detector will measure this radiation as a voltage. The voltage will be converted, using the system temperature, into an antenna temperature, which is proportional to the flux received from the source. An antenna temperature will be reported to you as a result of each of your observations.

In the example, we have chosen to move the antenna to Jupiter. We will use Jupiter to measure two values. The first, the *System Temperature* (T_{sys}), will be measured when the antenna has actually moved away from Jupiter. This is done to allow us to measure noise from the receiver and related equipment, and noise from an area of the sky that has no known source (like Jupiter). The Umbrella command to initiate a system temperature measurement is simply **Cal** (calibration)

The calibration is done by a comparison of the view of the sky at the feedhorn (and its measured voltage) and a view of a piece of ambient-temperature microwave absorber material that is moved in front of the feedhorn for a specified period of time (normally ten seconds). Since the absorber is at roughly ambient temperature (we actually assign a value of 300°K) and therefore a “known” value, we simply compare the voltage level in the receiver while looking at the sky to the level while looking at the absorber (also known as the “vane”). The ratio of the observed voltages (or noise) will convert to a system temperature based on the assigned value of the absorber.

The derived system temperature or calibration temperature is our noise baseline. We assign a nominal value of 0°K to this calibrated temperature when we move back to Jupiter to measure the flux of the planet. Any noise contribution from the planet itself will also be converted to a temperature value (also °K) over and above the calibrated temperature (now assigned as our 0°K noise base) to arrive at the *Antenna Temperature* (T_{Ant}) of the source.

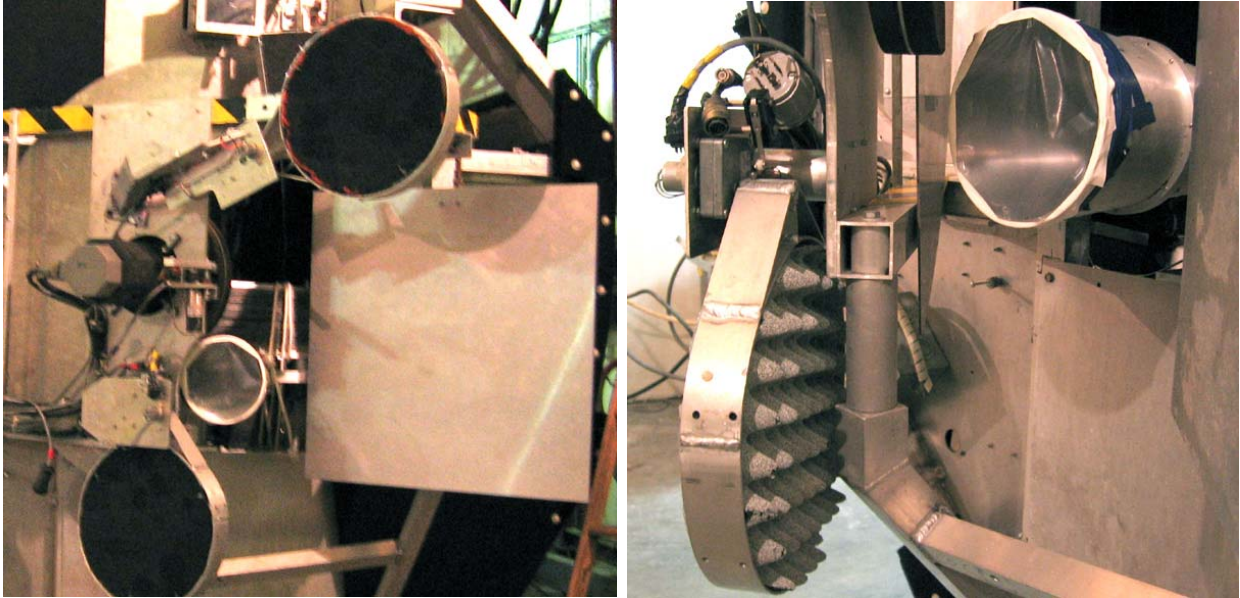
Example:

Tune the receiver to frequency - 22 GHz

```
Umbra> project = CHAUTAUQUA  
Umbra> maintenance = Off  
Umbra> frequency = 22000000  
Umbra> cdpmode = 1u  
Umbra> bandwidth = 160  
Umbra> inttime = 1  
Umbra> sourcelist = chautauqua.lst
```

```
Umbra> source = jupiter
```

```
Umbra> cal
```



The two images above are views of the front of the radiometer equipment box deployed on the telescope when it is configured for radio astronomy. The circular cone at the upper right of the right-side image is the feed-horn for the 36-49 GHz receiver. The feed-horn can also be seen to the lower left-of-center in the left-side image. The images also give you two views of the “vane” calibrator. The left-side view is the radiometer box as seen from the direction of the sub-reflector. As the calibration signal is given to the computer, the lower calibrator (the dark circular absorber below the 36-49 GHz feed-horn) will pivot up to block the feed. After ten seconds it will return to the retracted position for the “on-sky” comparison measurement.

2. Pointing Corrections using Discrete Source Scan (DSS)

Having finished our calibration and characterization of the system temperature, we now need to derive pointing offsets before we begin our observing plan. The 37-meter telescope has a pointing model based on the translation from celestial coordinates to azimuth-elevation coordinates. The model attempts to include corrections for instrumental errors such as the tilt of the azimuth plane from horizontal, the fact that the azimuth and elevation axes are not actually orthogonal, gravitational deformation of the dish and thermal errors that may displace the beam from the optical axis (collimation). These errors are accounted for (mostly) by checking the pointing accuracy on strong radio sources as they transit the sky. Data is collected from as many different azimuth-elevation positions as possible. A least squares fit determines the correction to the pointing parameters and the model is updated.

Pointing errors can also be caused by daily temperature changes especially when the radome environment changes beyond our capacity to control temperature (usually solar heating during summer days). To be certain that we are actually pointing on our selected source, it is prudent to check the pointing at the start of observations and at intervals throughout the observing run.

The umbrella command to initiate a pointing measurement is **DSS**. A discrete source scan moves the telescope in a roughly 0.2 degree azimuth scan centered on the computer position of the selected source (Jupiter in our example). As the telescope scans across Jupiter, the radiometer records the increase in flux as Jupiter passes through the telescope beam. A Gaussian fit of the flux data reports a peak flux signal as a function of the azimuth position in degrees. The peak may or may not be at the computer azimuth position for the source. If there is an observed offset from the computer position, that offset is sent to the encoder and the telescope is moved accordingly. The telescope then performs a scan in the elevation direction. As before, a Gaussian fit is made to the flux data and any offset is reported to the user on the Umbrella screen.

The basic set of Umbrella commands are as follows: (It is assumed, of course, that you have followed the tutorial to setup the radiometers and calibration steps before the DSS. In any case, the Umbrella software will not allow you to take DSS data unless you have calibrated and are actively pointed on a source)

```
Umbrla> source = jupiter  
Umbrla> bandwidth = 160  
Umbrla> inttime = 1  
Umbrla> dss
```

After the DSS run, a table will be generated in the Umbrella Xterm window. This table reports the amplitude of the observed flux as well as the azimuth and elevation pointing offsets (in degrees) labeled as **Usroffs**. The table below shows the last few lines of the text output of the azimuth and elevation that is printed to the Umbrella xterm window. The graphical output of the scan can be generated by typing at any system xterm prompt:

```
chautauqua@fourier% Xtterm D
```

At the end of the DSS run, enter the derived offsets by typing

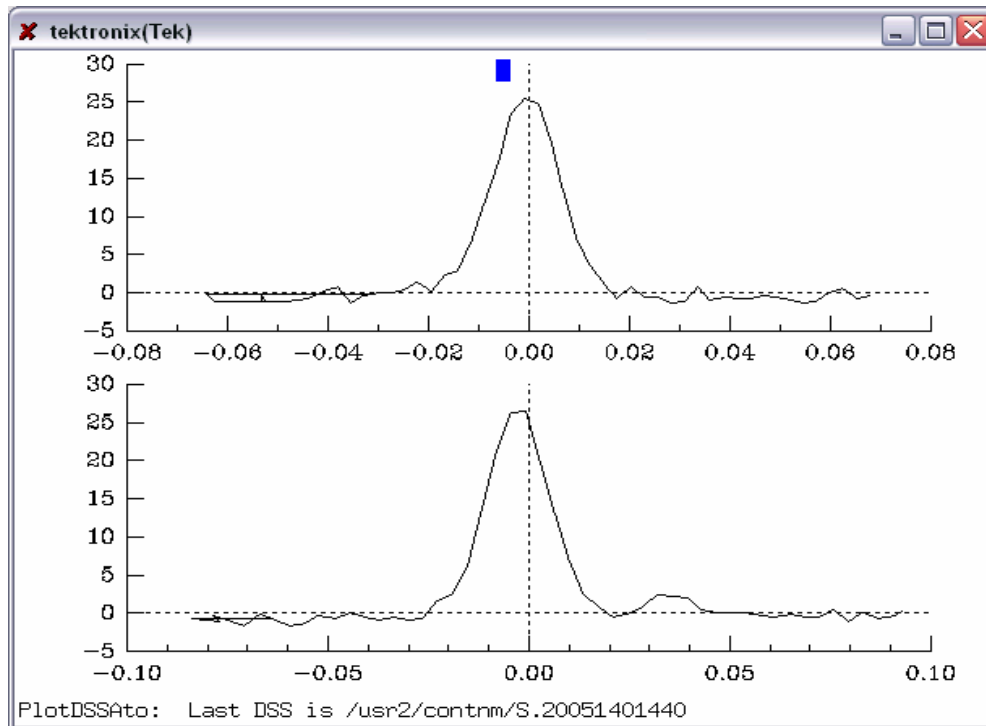
```
Umbrla> Usroffs = +/- .nnn +/- .nnn (in this case, 0.0103 -0.0014)
```

You should always run a second DSS measurement to verify your results

```

Xterm Umbra
140 14:41:41.4 -0.753 0 0 0 -0.0000 0.0440 0.0001 -0.0002
140 14:41:42.4 -0.386 0 0 0 -0.0002 0.0466 0.0001 -0.0002
140 14:41:43.4 -0.485 0 0 0 -0.0001 0.0492 0.0001 -0.0002
140 14:41:44.4 -0.972 0 0 0 -0.0000 0.0521 0.0000 0.0001
140 14:41:45.4 -1.346 0 0 0 -0.0002 0.0544 0.0002 -0.0002
140 14:41:46.4 -1.082 0 0 0 -0.0000 0.0570 0.0001 -0.0002
140 14:41:47.4 0.112 0 0 0 -0.0001 0.0596 0.0001 -0.0002
140 14:41:48.4 0.615 0 0 0 -0.0001 0.0623 0.0001 -0.0001
140 14:41:49.4 -0.805 0 0 0 -0.0000 0.0656 -0.0001 0.0005
140 14:41:50.4 -0.443 0 0 0 -0.0001 0.0678 -0.0006 0.0048
Umbra DSS end E1 scan
----Baseline-----Gaussian-----
Offset Slope Amplitude Position Width
-0.6476 0.0000 26.5212 -0.0009 0.0132 DEBUG Guesses
-0.4225 -1.6411 26.3883 -0.0005 0.0155 5 GOOD
0.0947 2.4866 0.3188 0.0001 0.0002 0.6699 RMSs
To use these DSS offsets for subsequent observing,
change to: UsrOffs = 0.0103 -0.0014
Umbra wrote DSS data file /usr2/contnm/S.20051401440
Umbra>

```



3. 37-Meter Focus procedure

A focus measurement can be performed by the user as a check to determine that the subreflector is positioned properly along the optical axis from the center of the subreflector to the center of the feedhorn.

The subreflector actually can perform seven different focus measurements. The "z-axis" translation (think of an **x,y,z** cartesian system where **x** moves the subreflector left or right as seen from the feed, **y** moves the subreflector up and down and **z** moves toward or away from you) is the only one that you should attempt to measure prior to observing since a complete set of focus measurements (used to optimize and update the subreflector setup parameters) requires several days of optimum weather and temperature conditions.

Umbrella focus modes: (command **focusmode=n**)

- 1 - Z axis translation (focus)
- 2 - Astigmatism
- 3 - Y-axis (elevation) translation (up and down)
- 4 - Y-axis tilt
- 5 - X-axis (azimuth) translation (left and right)
- 6 - X-axis tilt
- 7 - C-Ring displacement (deformation)

The actual user measurement (number 1 above) requires that you are **well-pointed** (see section 2) on a bright point source (example, RLeo at the 7mm SiO frequency). You then set parameters in the Umbrella focus measurement setup to take total power measurement of the flux of the source at three different positions **along the optical axis** from the feed to the subreflector. You select an arbitrary position near the default value (**focuscenter=n** derived from previous, in-house focus tests) and two other positions an equal distance (with opposite signs) from the selected center position (**focusstep=n**). These offsets should be some large fraction of the observing wavelength (in this case~7mm) that when the subreflector is de-focused to that position, you would observe a drop in the measured flux value by roughly half.

You would then take a selected integration time (**inttime=n**) of data at each of the three subreflector positions. The flux measurements are averaged over the user-selected number of data points (**npoints=n**) at each position. The three resulting measurements; negative out-of-focus, center "focus" and positive out-of-focus are fit to a curve, the peak of which is defined as the best focus position (**Subtrans=n**).

In the past, we have conducted all the focus measurements as an engineering exercise before any observations were done and directed the users that we had the subreflector "optimized" for the ideal observing conditions of clear weather and a thermally stable radome environment.

Since we now do student observing during the summer daytime and the subreflector has some of its actuators offline, a Z-axis focus check is good practice at the start of daytime observing and as the radome approaches temperature stability in the evening or temperature instability as daytime heating becomes uncontrolled (during very warm summer days, the radome rarely stabilizes overnight!)

Setup example:

Our current focus position default (for the 7mm receiver) is: -145

You would select in Umbrella:

```
Umbrella>FocusMode = 1
Umbrella>FocusCenter = -200
Umbrella>FocusStep = 200 *These numbers represent mils (.001 inches)
                          273 represents ~7mm
Umbrella>Inttime = 1 * 1 second per point
Umbrella>npoints = 10 * Or some other value (at least 5)
Umbrella>cal
Umbrella>focus
```

The result will display the antenna temperature average from each point and a resulting curve-fitted value for the best focus number. If the result is much different from -200 (say 50 or more) measure the focus again ([you should always do two!](#))

```
Xterm Umbrella
Umbrella> cal
Umbrella doing cal
Umbrella waiton() active checking ...
Umbrella waiton() now reports OK
Umbrella: tbase[] = 197.94 0.00 0.00 0.00 K
Umbrella> focus
Umbrella doing focus
setpos() set focus (Z offset) to -400.000000
Umbrella waiton() active checking ...
Umbrella WARNING: LDRF box is not updating
Umbrella waiton() now reports OK
140 19:21:15.4 21.835 0 0 0 -0.0006 0.0004 0.0005 0.0003
140 19:21:16.4 21.150 0 0 0 -0.0006 0.0004 0.0005 0.0003
140 19:21:17.4 20.933 0 0 0 -0.0006 0.0003 0.0005 0.0002
140 19:21:18.4 22.784 0 0 0 -0.0006 0.0003 0.0005 0.0002
140 19:21:19.4 23.265 0 0 0 -0.0005 0.0003 0.0005 0.0002
140 19:21:20.4 22.633 0 0 0 -0.0005 0.0003 0.0004 0.0002
140 19:21:21.4 22.878 0 0 0 -0.0004 0.0003 0.0004 0.0002
140 19:21:22.4 22.534 0 0 0 -0.0004 0.0002 0.0003 0.0001
140 19:21:23.4 23.142 0 0 0 -0.0003 0.0003 0.0003 0.0002
140 19:21:24.4 23.497 0 0 0 -0.0004 0.0003 0.0004 0.0002
140 19:21:25.4 22.593 0 0 0 -0.0003 0.0001 0.0003 0.0001
140 19:21:26.4 21.032 0 0 0 -0.0003 0.0002 0.0002 0.0002
setpos() set focus (Z offset) to -200.000000
Umbrella waiton() active checking ...
Umbrella WARNING: Subreflector status is Waiting
Umbrella waiton() now reports OK
140 19:21:42.4 46.609 0 0 0 0.0001 0.0002 -0.0000 0.0002
140 19:21:43.4 47.221 0 0 0 -0.0000 0.0001 0.0000 0.0001
140 19:21:44.4 46.448 0 0 0 -0.0001 0.0000 0.0000 -0.0000
140 19:21:45.4 47.229 0 0 0 0.0001 0.0002 -0.0000 0.0002
140 19:21:46.4 45.938 0 0 0 0.0002 0.0001 -0.0001 0.0001
140 19:21:47.4 45.247 0 0 0 -0.0001 0.0000 0.0001 0.0000
140 19:21:48.4 44.288 0 0 0 0.0002 0.0000 -0.0001 0.0000
140 19:21:49.4 45.360 0 0 0 0.0000 0.0001 0.0000 0.0001
140 19:21:50.4 44.961 0 0 0 -0.0000 -0.0000 0.0000 -0.0000
140 19:21:51.4 44.989 0 0 0 -0.0001 0.0001 0.0001 0.0001
140 19:21:52.4 45.310 0 0 0 -0.0000 0.0000 0.0000 0.0000
140 19:21:53.4 45.436 0 0 0 -0.0005 0.0001 0.0004 0.0000
setpos() set focus (Z offset) to 0.000000
Umbrella waiton() active checking ...
Umbrella WARNING: Subreflector status is Waiting
Umbrella waiton() now reports OK
140 19:22:08.4 32.762 0 0 0 0.0001 -0.0001 -0.0001 -0.0001
140 19:22:09.4 33.462 0 0 0 -0.0001 -0.0000 0.0001 -0.0000
140 19:22:10.4 33.180 0 0 0 -0.0001 -0.0000 0.0001 -0.0000
140 19:22:11.4 33.734 0 0 0 -0.0000 -0.0000 0.0000 -0.0000
140 19:22:12.4 33.634 0 0 0 -0.0001 -0.0000 0.0001 -0.0001
140 19:22:13.4 33.573 0 0 0 -0.0001 -0.0000 -0.0001 -0.0000
140 19:22:14.4 33.578 0 0 0 -0.0002 -0.0001 -0.0002 -0.0000
140 19:22:15.4 33.986 0 0 0 -0.0000 -0.0000 0.0000 -0.0000
140 19:22:16.4 33.761 0 0 0 0.0000 -0.0001 0.0000 0.0000
140 19:22:17.4 33.761 0 0 0 0.0001 -0.0000 -0.0001 0.0000
140 19:22:18.4 33.604 0 0 0 0.0000 -0.0000 -0.0000 -0.0000
140 19:22:19.4 34.066 0 0 0 -0.0001 0.0001 0.0001 0.0001
Temperatures to be fitted: 22.356 45.753 32.874
Position = -163.162, Width = 460.335, Peak = 46.573
setpos() set focus (Z offset) to -210.000000
Umbrella wrote Focus data file /usr2/contnm/F.20051401921
Umbrella: End of Focus
Umbrella>
```

If the result is very different, >200, then the measurement is probably bad. The center average MUST be higher than the two offsets for a useful measurement.

The focus **result** can be read from the line in the screen capture that reads **Position =**

You would enter the result (that you trust) in Umbrella using:

Umbra>**SubTrans = result** (-163 in this example)

Any subsequent change in frequency would cause the focus value to revert to the default number.

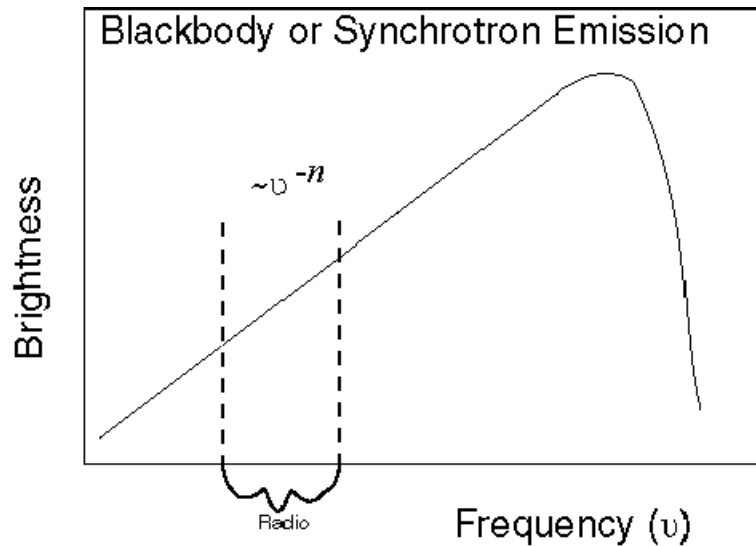
EXAMPLES OF UNDERGRADUATE ACTIVITIES USING THE HAYSTACK OBSERVATORY 37-METER RADIO TELESCOPE

A study of thermal and non-thermal radio emission mechanisms.

Your project is to study the nature of radio continuum emission from astrophysical sources. The goal of this project is to understand the difference between various emission mechanisms that produce radio emission. To this end, you will observe and record data from three different astrophysical sources using the 36.6 meter radio antenna (telescope) at the MIT Haystack Observatory in Groton, MA.

Introduction

Radio sources fall broadly into two main categories -- thermal sources and non-thermal sources. The mechanism for producing the radio emission is different in these two categories. Thermal sources emit blackbody radiation:



If a source is at a particular temperature, then its spectrum (measured flux as a function of wavelength or frequency) is defined by the Planck blackbody equation. This equation describes the familiar shape of any blackbody curve. As illustrated above, the shape of this curve is different on each side of its peak. On the less steep side, called the Rayleigh-Jeans side, the frequency dependence of the flux is given by:

$$(1) \quad S_{\nu} = CT_b \nu^2$$

Here T_b is the brightness temperature, which is defined as the Rayleigh-Jeans temperature of an equivalent blackbody which will give the same power per unit area per unit frequency as the astronomical source. In plain English, this means that there is only one blackbody curve which will give exactly this much flux at this frequency, and T_b is the temperature of a source which would have this blackbody curve as its spectrum. The C in the equation is a constant of proportionality.

Radio emission from thermal sources usually falls on the Rayleigh-Jeans side of the curve, so the equation above shows that the radio flux from a thermal source is proportional to the square of the radio frequency.

The motion of electrons around magnetic field lines produces non-thermal emission (cyclotron). If the motions are relativistic (at speeds close to the speed of light), the phenomenon is called synchrotron. Synchrotron emission also has a characteristic frequency dependence:

$$(2) \quad S_\nu = K \nu^{-0.7}$$

(note the negative power). Most non-thermal emission from radio sources is synchrotron emission.

For all sources, we can write the frequency dependence of the flux as follows:

$$(3) \quad S_\nu = K \nu^n$$

where S_ν is the flux, K is the constant of proportionality (which now includes T_b , so $K = CT_b$), and n is called the spectral index.

The spectral index defines the slope of the flux vs. frequency curve. If you take the log of both sides of the above equation, you will get:

$$(4) \quad \log(S_\nu) = n \log(\nu) + \log K$$

This equation is now in the familiar form of a straight line ($y = mx + b$), where m is the slope of the line and b is the y-intercept. This is called *linearizing* the equation. Knowing this slope can determine the nature of the emission mechanism for the particular source.

For our equation, y is $\log(S_\nu)$, slope m is n , x is $\log(\nu)$ and b is $\log K$. For example, a slope of 2 suggests thermal blackbody emission ($S_\nu = K\nu^2$). By measuring the intensity (flux) of the emission from the source at several frequencies, the slope of the blackbody curve can be measured.

The best thermal sources to observe are planets. You will observe Saturn as your thermal source. Good strong non-thermal sources are supernova remnants or some quasars. You will observe the supernova remnant known as the Crab Nebula.

In this experiment, you will first use the emission from a planet (Jupiter) to calibrate the telescope. This means that you will determine how your measurements from the telescope correspond to what is really emitted by an observed object by first measuring an object whose flux is already known. Then you will observe two sources (Saturn and the Crab Nebula) at two different frequencies (22 GHz and 43 GHz) and solve for the spectral index of each source.

A. Spectral Index Measurements of Continuum Sources

1. Get a measure of the system temperature.

This is not a physical temperature but rather a calibration step. When the telescope receives radiation, the detector will measure this radiation as a voltage. The voltage will be converted, using the system temperature, into an antenna temperature, which is proportional to the flux received from the source. An antenna temperature will be reported to you as a result of each of your observations.

Tune the receiver to frequency - 22 GHz

```
Umbra> project = CHAUTAUQUA  
Umbra> maintenance = Off  
Umbra> frequency = 22000000  
Umbra> cdpmode = 1u  
Umbra> bandwidth = 160  
Umbra> inttime = 1  
Umbra> sourcelist = chautauqua.lst
```

```
Umbra> source = jupiter
```

```
Umbra> cal
```

2. Get a measure of the aperture efficiency at 22 GHz.

The aperture efficiency of a telescope is a measure of what percentage of the radiation, which falls on the telescope from an astronomical source, is actually received by the detector attached to the telescope. Aperture efficiencies depend on the frequency of observation and can vary from 30% to 40 % at the Haystack telescope.

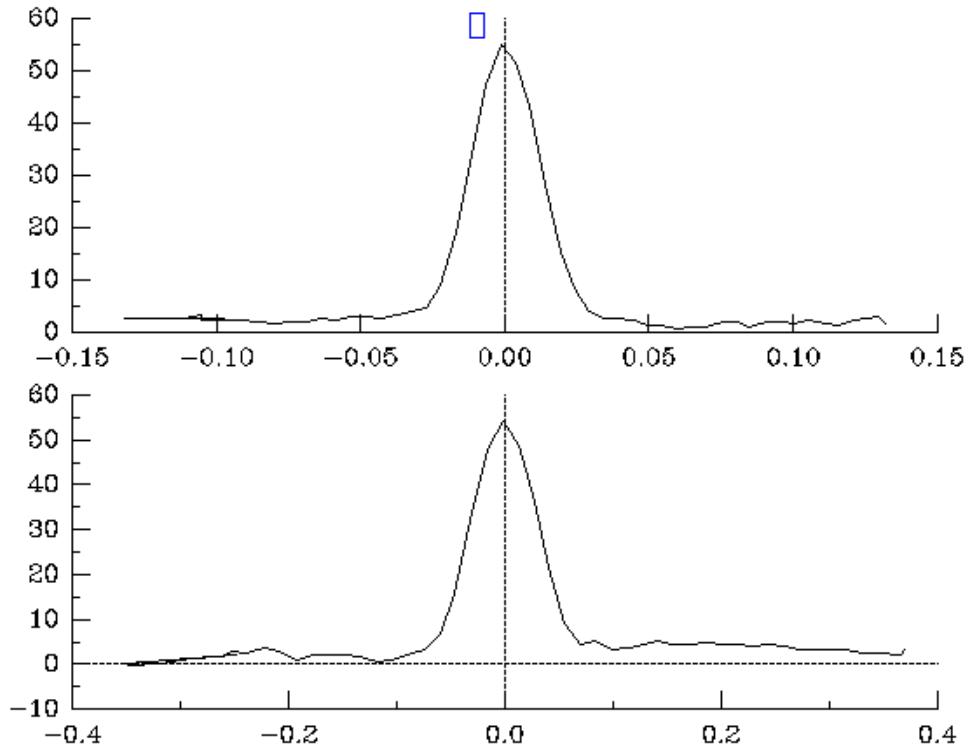
To measure the aperture efficiency, observe Jupiter at 22 GHz using a discrete source scan (DSS). In this method, the telescope steps across the source in azimuth and in elevation and fits a Gaussian curve to the emission from the planet.

```
Umbra> dss
```

You can see a graphical DSS output by typing

```
chautauqua@fourier% Xterm D * Caps required here
```

in the **Color Xterm** window (Where you started the session)



PlotDSSAt0: Last DSS is /usr2/contnm/S.20001391059

The peak value of the Gaussian curve will be the antenna temperature of Jupiter. This number will be input into the "efcal" program, which will output the aperture efficiency by comparing the known flux from Jupiter to the flux measured by our telescope.

chautauqua@fourier% **~jball/bin/efcal**

Push the "Enter" key at the DATE

Type in your Frequency in MHz (**22000.000**)

Type in the Planet number (Jupiter = **5**)

Type in the Antenna Temperature reported by the DSS result (**2nd** number under "Amplitude")

The decimal answer will be **~.350-.400** or 35-40 % aperture efficiency

3. We now want to determine the brightness temperature of Saturn at 22 GHz, which will in turn give us Saturn's flux.

In order to do this, observe Saturn at the same frequency using the same DSS method as above and obtain its antenna temperature. Divide the antenna temperature by the aperture efficiency to get the brightness temperature of Saturn.

```
Umbra> source = saturn  
Umbra> cal  
Umbra> dss
```

4. Repeat steps 2 and 3 for a frequency of 43.000 GHz.

Stay on Saturn

```
Umbra> frequency = 43000000
```

```
Umbra> cdpmode = 1m  
Umbra> beamswitch = on  
Umbra> cal  
Umbra> dss
```

Go to Jupiter

```
Umbra> source = jupiter  
Umbra> cal  
Umbra> dss
```

Find the Aperture Efficiency of Jupiter (see #3)

5. Convert the brightness temperatures to fluxes (S_ν) in units of Janskys (watts per meter squared *per hertz*). (This flux is *per unit frequency*; the flux we talk about in class is total flux integrated over all frequencies, so its units are just watts per meter squared.) This can be done using the following equation:

$$(5) \quad S_\nu = 8.19 \times 10^{-7} \times T_b \times \theta''^2 \times \nu(\text{GHz})^2$$

Here θ is the beamsize given by $1.22\lambda/D$ (what units does this give?). You **MUST** insert the quantities in the units shown in order for this equation to yield correct results.

6. The spectral index can now be obtained by solving the linearized form of the equation $S_\nu = K \nu^n$ as given above (eqn.(4)) using the fluxes found at the two frequencies (see attached worksheet).

B. Spectral Index for Crab Nebula (NGC1952 - M1)

This entire experiment can now be repeated for a non-thermal source such as the Crab Nebula. In order to obtain the antenna temperature of the Crab Nebula, we need to make a *map* of the source. This is done by a method known as a *drift scan*. The basic idea is that the telescope stays still while the source drifts across the sky due to the earth's rotation. In more typical observing methods, the telescope moves at the same rate as the observed object moves across the sky (this is called *tracking*), so the telescope is always looking at the same part of the object. In drift mode, the telescope is always looking in the same direction (it is not moving), so it sees different parts of the object over time as the object moves across the sky. This allows the observer to *map* the whole object. The antenna temperature is read off the plot that is made as a result of this scan. Examples are shown on the next page.

Tune the receiver to the frequency of 22.000 GHz

```
Umbrla> frequency = 22000000  
Umbrla> cdpmode = 1u
```

Make a map of the Crab Nebula

```
Umbrla> source = CrabN 05 34 31.44 22 00 52 2000 0  
Umbrla> cal  
  
Umbrla> cdpmode = 1m  
Umbrla> inttime = 1  
Umbrla> npairs = 1  
Umbrla> swoff = -0.1 .048  
Umbrla> npoints = 25  
Umbrla> duration = 40  
Umbrla> spacing = .004  
  
Umbrla> drift
```

An explanation of Drift-Scans

The Umbrella commands above; **swoff**, **npoints**, **duration** and **spacing** set the drift-scan map parameters. The drift-scan method is designed to minimize the effects on the source signal strength of the radome structural members. Because the map orientation is in Right Ascension and Declination the telescope is moved to an initial Ra and DEC offset position (**swoff**). For clarity, this position would be the "northwest" corner of the scan area as viewed on the sky. The telescope is then parked for a specified time period in seconds (**duration**) to allow the source to "drift", with the earth rotation, through the beam. When the first drift scan is completed the telescope adjusts position in declination (**spacing**) and moves westward (negative RA) by the angle specified in the first **swoff** parameter. It then observes another drift scan. The process is

repeated for the number of scans specified by **npoints**. In this case the map will be completed in about 20 minutes.

The output data file label format is:

D.yyyydddttt

Where, **yyyy** = year
 ddd = day number
 ttt = UT start time

The output data file name will appear in the "Xterm log" window at the commencement of the mapping scan and in the "Xterm Umbra" window at the end of the scan. When the scan is complete, you will invoke a graphical plotting program known as PGPlot to view the completed map.

In the "Color Xterm" window, type:

```
chautauqua@fourier% source setup.fourier
```

```
chautauqua @fourier% ~reb/MDS/dmap x/D.yyyydddttt 0 - col
```

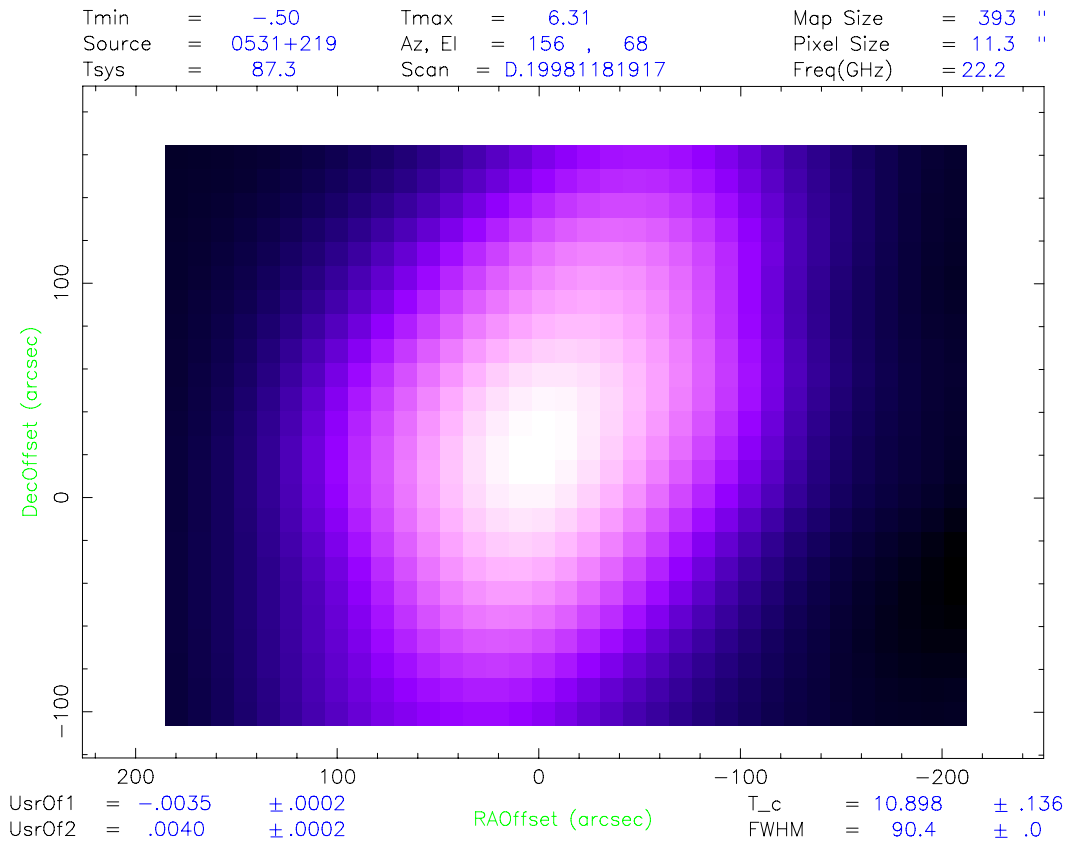
A PGPlot map of Crab Nebula will appear in ~5 seconds. The output map will appear similar to the example shown below. Moving the mouse to the on-screen plot area and pushing the left mouse button one time will invoke the plot labels.

Typing "q" in the Color Xterm window will "freeze" this window plot to a file labeled pgplot.ps. ***This pgplot.ps file will be overwritten by subsequent maps OR by re-issuing the plot syntax in the Color Xterm window!***

Alternately you can use the following scripts (which are resident on the chautaugua sub-directory in Fourier) to produce the PGPlot window image.

```
chautauqua@fourier% DriftMap           (for frequencies < 40 GHz)
```

```
chautauqua@fourier% DriftMap-plus   (for frequencies > 40 GHz)
```



If the plot is satisfactory and you now wish to save the plot to a postscript file, go to the **Color Xterm** window and type:

```
chautauqua @fourier% cp pgplot.ps 22crabmap.ps
```

or whatever file name type is preferred. Be sure to remember to include the ".ps" postscript suffix.

Tune to Frequency of 43.000 GHz and repeat the Map.

```
Umbrla> frequency = 43000000
Umbrla> cdpmode = 1m
Umbrla> beamswitch = on
```

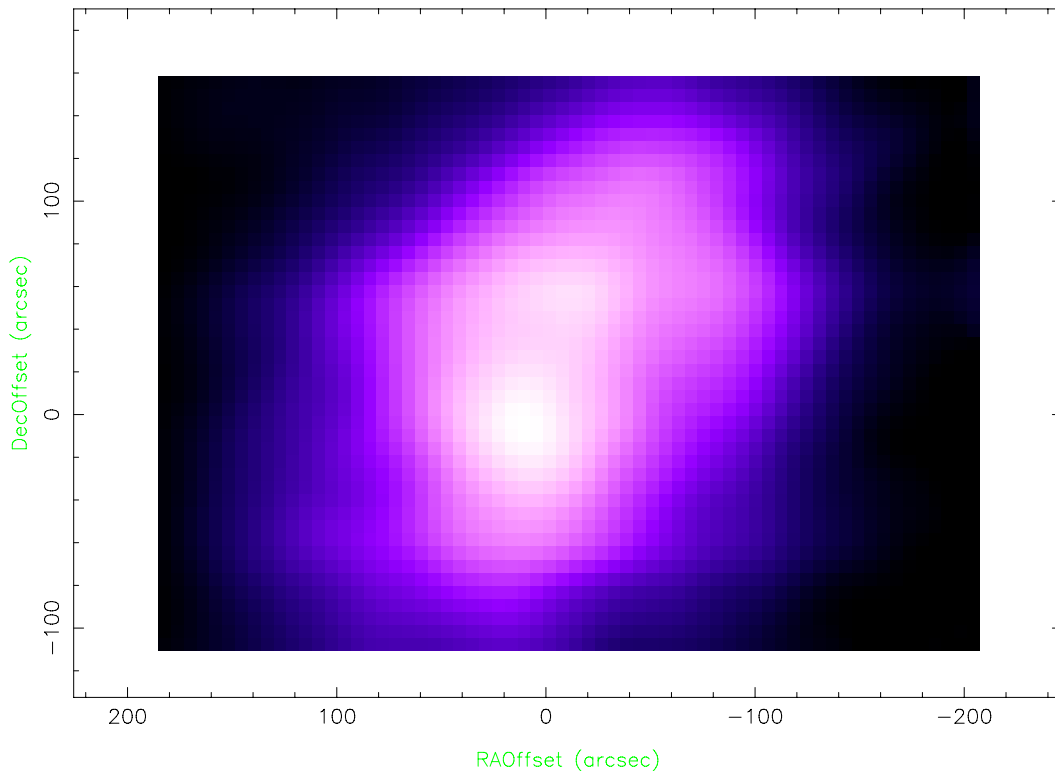
```
Umbrla> cal
```

```
Umbrla> inttime = 1
Umbrla> npairs = 1
Umbrla> swoff = -0.1 .048
Umbrla> npoints = 25
Umbrla> duration = 40
Umbrla> spacing = .004
```

```
Umbrla> drift
```

You will note that for the 43 GHz map, you are issuing the command `"beamswitch = on"`. The 43 GHz-range receiver (Q-Band or 7mm λ) has a beamswitching capability. That is a mechanical "half wheel" device that spins at a selected rate (normally 20 Hz) and alternately blocks and unblocks the receiver feed from the direct raypath of the source signal. When the wheel is in a blocking position it diverts the observing beam to an off-axis steel plate (essentially a mirror at this frequency) and forces the receiver to observe an area of the sky that is approximately -0.1 degrees in azimuth away from the source.

When this scan is finished, repeat the PGPlot command sequence with the *new* D.yyyyddttt filename.



You will notice that, because of the smaller beam size (~90 arcseconds vs ~55 arcseconds) that the resolution is higher in the 43.0 GHz map.

Determine the finished plot view and go to the xterm window and type:

```
chatauqua@fourier% cp pgplot.ps 43crabmap.ps
```

C. Measurement of Ammonia Line Emission

1. Tune to the NH₃(1,1) frequency at 23.694496 GHz

```
Umbra> frequency = 23694496
```

2. Go to the source NGC 7538

```
Umbra> source = NGC7538 23 11 36.6 61 11 48 1950 -58
```

3. Do two 5-minute frequency-switched scans (as described in your telescope handout) on your source position.

```
Umbra> frequencyswitch = on
```

```
Umbra> fregsoffs = 4450 -4450 -4450 * see the note below
```

```
Umbra> bandwidth = 17.8
```

```
Umbra> inttime = 10
```

```
Umbra> npairs = 1
```

```
Umbra> npoints = 1
```

```
Umbra> cdpmode = 1u
```

```
Umbra> cal
```

```
Umbra> sfs
```

This will produce one spectrum on NGC7538. In the Xterm Umbra window, you will see text lines that report every ten seconds as the correlator gathers the data. When the specified integration time is reached (the total integration time is **IntTime x 30 seconds**), the text will report the spectral observation is complete. The Xterm Umbra window will also print the spectral observation file name.

The file name will be of the form:

s.ryydddnnnn

Where, *r* = receiver #, *yyyy* = year, *ddd* = day number, *nnnn* = spectrum number for the UT day

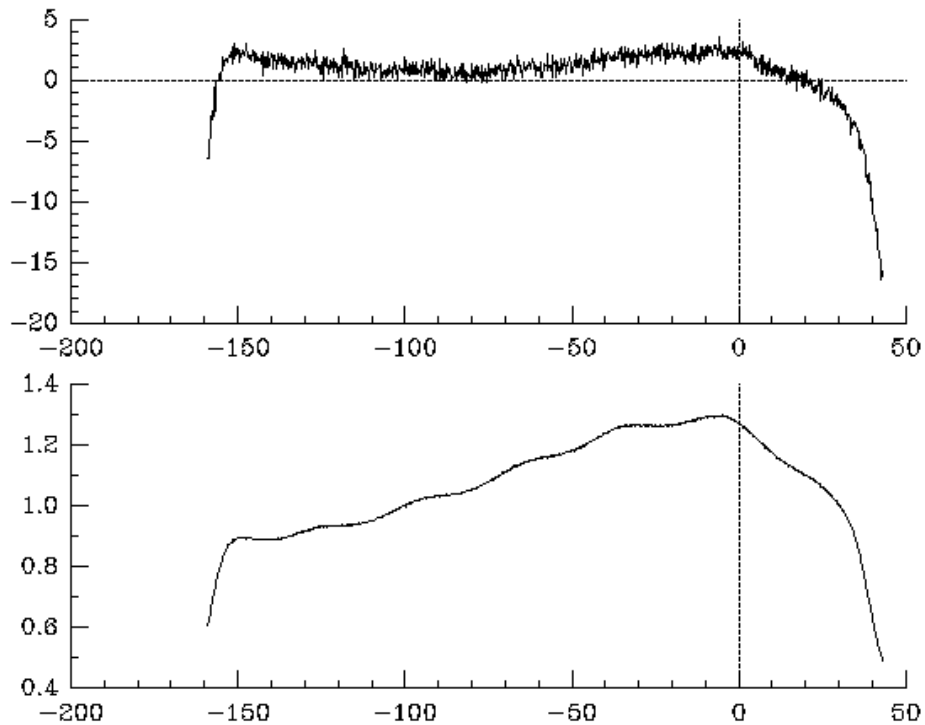
To look at the raw output, go to the Xterm Window and type:

```
chatauqua@fourier%>Xtterm 1
```

note: CAPS required here!

An output screen will appear similar to the graphical DSS. The lower half of the spectral display plot is the bandpass of the receiver at the selected bandwidth. A perfect bandpass would be a "square-wave" which as the name implies, should have straight vertical sides and a flat horizontal "top". The upper plot represents the "difference spectrum". When the observation is in progress

(using frequency switching), the spectral line is shifted alternately from one side of the bandpass to the other the signal without the spectral line is subtracted from the signal with the spectral line, hence the "difference spectrum".



PlotAto: Spectrum is /usr2/spectra/s.1001430004

To do the second spectrum, type:

```
Umbrla> cal  
Umbrla> sfs
```

4. Tune to the NH₃(2,2) frequency at 23.722632

```
Umbrla> frequency = 23722632
```

Repeat step #3

You may need to acquire 3-5 NH₃ (2,2) spectra!

A note about Frequency Switching

The 4-digit offsets used in the *Freqsoffs* = command for these observations are derived by the formula:

Observing bandwidth / 4 x 1000

Or when the Bandwidth = 17.8

17.8/4 = 4.450 x 1000 = 4450 = nnnn

D. Running the CLASS Data Reduction Program

1. In one of the unused computer environment windows, open two xterm windows to begin the data reduction portion of the NGC7538 ammonia observations. Position the xterm windows side by side at the top of your screen.

In the lower right corner of the LINUX control console there is a gray-colored 2 x 2 box. The upper left box will show a depiction of the layout of your current work area. To select a new work area click on one of the five remaining boxes to open a blank screen (new work area) and then click on the **xterm** button on the toolbar twice.

2. To create a file readable by the CLASS data reduction program, go to one of the two xterm windows and type:

```
chautauqua@fourier%>AutoCLASS * Caps required here!
```

This will create the file -- *class.04ddd* that you will need for the DATA REDUCTION portion of the observations. All the spectra generated by today's observations will automatically be CLASS formatted and included into the *class.04ddd* file.

Where; *04* denotes the year and *ddd* is the day number (in Universal-UT)

3. In the other xterm window, type:

```
chautauqua@fourier%> Class * Note capital C
```

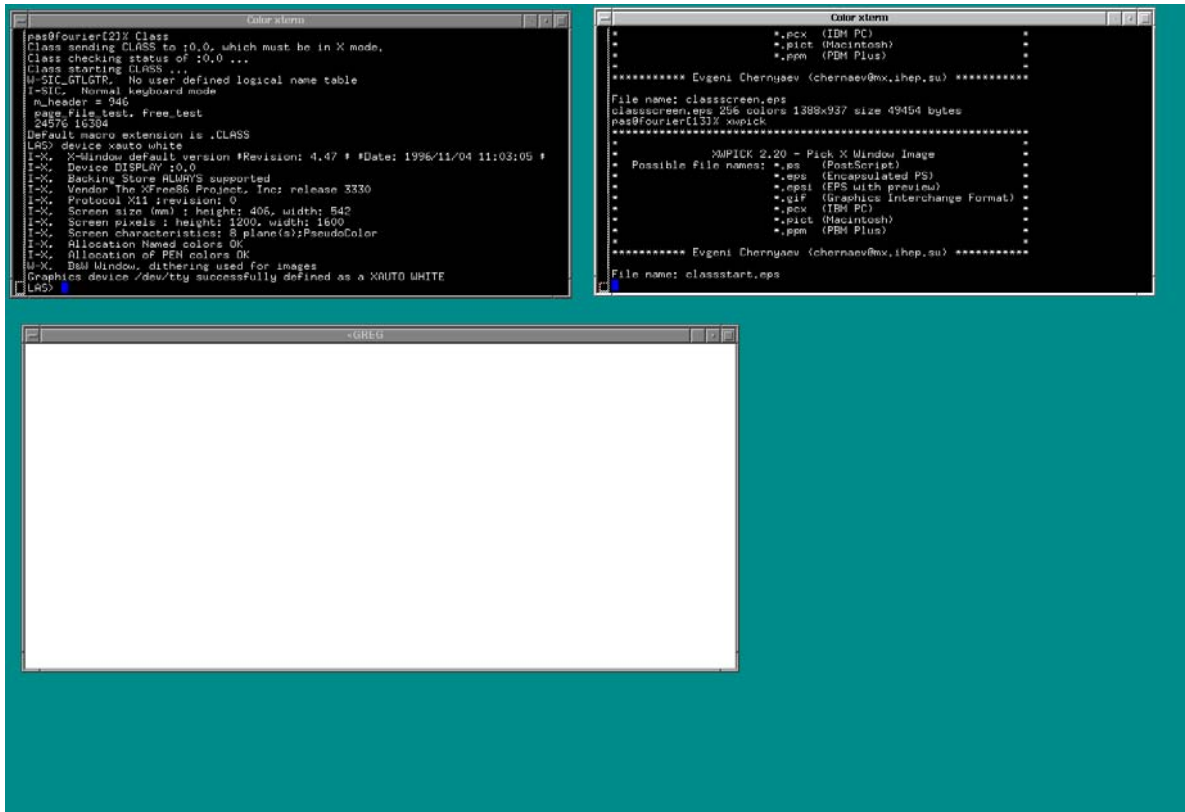
This will start the CLASS data reduction program and will open a prompt labeled:

```
LAS>
```

4. At the LAS> prompt, type:

```
LAS> device xauto
```

This action will open a large white display window for the class format spectra files generated from today's observations. The workstation display should look something like the figure below.



When **AutoCLASS** (or **GetCLASS**) has generated an active file for your data, you may open it in the CLASS program with the following command:

```
LAS> file in class.04nnn
```

To list the file contents:

```
LAS> list in
```

You will see a printout in the class window similar to the window below:

```
Xterm fourier
page_file_test, free_test
24576 16384
Default macro extension is .CLASS
LAS> file in class.04101
I-CONVERT, File is [Native]
I-INPUT, class.04101 successfully opened
LAS> list in
I-LISTE, Input file contains :
  1; 1 IRAS  NH3 1(1)-1(1 HAYSTACK 120  0.0  0.0 Eq*****
  2; 1 IRAS  NH3 1(1)-1(1 HAYSTACK 120  0.0  0.0 Eq*****
  3; 1 IRAS  NH3 1(1)-1(1 HAYSTACK 120  0.0  0.0 Eq*****
  4; 1 IRAS  NH3 1(1)-1(1 HAYSTACK 120  0.0  0.0 Eq*****
  5; 1 IRAS  NH3 1(1)-1(1 HAYSTACK 120  0.0  0.0 Eq*****
  6; 1 IRAS  NH3 1(1)-1(1 HAYSTACK 120  0.0  0.0 Eq*****
  7; 1 IRAS  NH3 1(1)-1(1 HAYSTACK 120  0.0  0.0 Eq*****
  8; 1 IRAS  NH3 1(1)-1(1 HAYSTACK 120  0.0  0.0 Eq*****
  9; 1 IRAS  NH3 1(1)-1(1 HAYSTACK 120  0.0  0.0 Eq*****
 10; 1 IRAS  NH3 1(1)-1(1 HAYSTACK 120  0.0  0.0 Eq*****
 11; 1 IRAS  NH3 1(1)-1(1 HAYSTACK 120  0.0  0.0 Eq*****
 12; 1 IRAS  NH3 1(1)-1(1 HAYSTACK 120  0.0  0.0 Eq*****
 13; 1 IRAS  NH3 1(1)-1(1 HAYSTACK 120  0.0  0.0 Eq*****
 14; 1 IRAS  NH3 1(1)-1(1 HAYSTACK 120  0.0  0.0 Eq*****
 15; 1 IRAS  NH3 1(1)-1(1 HAYSTACK 120  0.0  0.0 Eq*****
 16; 1 IRAS  NH3 1(1)-1(1 HAYSTACK 120  0.0  0.0 Eq*****
LAS>
```

To select a frequency-switched file for display (EXAMPLE):

```
LAS> get 1
```

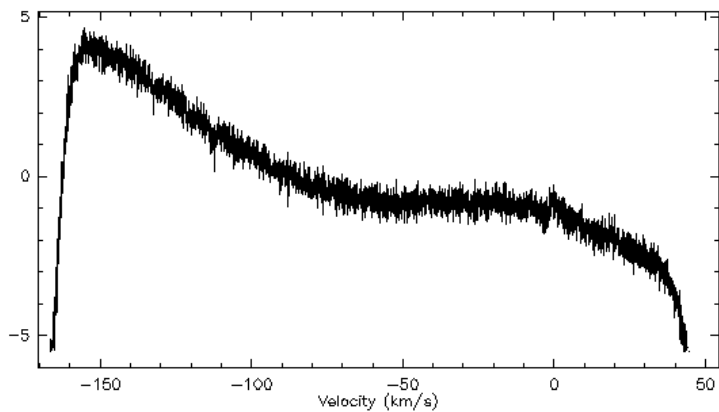
Where, the 1 is the spectra order number in the previous command

If you were to plot the raw frequency-switched spectrum using the Class command:

```
LAS> plot
```

The uncorrected or "raw" output would look similar to the plot seen below:

3; 1 NGC7538 NH3 1(1)-1(1 HAYSTACK 120 -0.673 -2.000 Eq*****



To correct the frequency-switched spectrum for display:

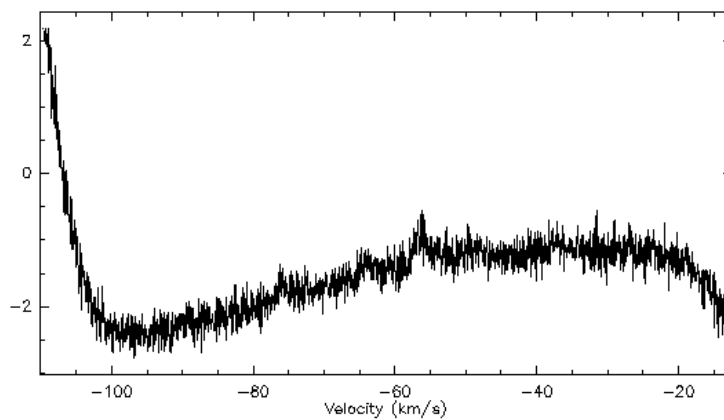
LAS> [fold](#)

To display the folded spectrum

LAS> [plot](#)

The white plot window should display the NH3 spectrum as follows:

3; 1 NGC7538 NH3 1(1)-1(1 HAYSTACK 120 -0.673 -2.000 Eq*****



To sum several observations use the following Class commands. **You can only sum spectra of the same frequency and observing bandwidth!**

```
LAS> find [parameters]
LAS> sum
LAS> fold
LAS> plot
```

***** For Example: *****

After the first three spectra are entered into a class.00ddd file, you might follow these commands:

```
LAS> find /all
Or
LAS> find /number 1 3
```

A message will print in the input window saying "*3 observations found*"

To list the observations found, type:

```
LAS> list
```

The window will then display the list of three observations in the index, then type:

```
LAS> sum
LAS> fold
LAS> plot
```

For a full header list on the output plot

```
LAS> set format long
LAS> plot
```

The summing of the multiple spectra will still have the curved baseline seen in the previous plot display.

You now want to remove the receiver response from your spectrum by fitting and subtracting a polynomial baseline. At this point you want to select the left and right of the area you DON'T want to include in your baseline fit - such areas would include the edges of the band and the lines.

There are several Class commands needed to correct or "flatten" this baseline for a proper display and analysis.

```
LAS> set cursor
LAS> set window
```

Using the mouse pointer and the "n" key, set boundaries on the baseline areas to be included in the fit. You would put your vertical cursor to the left of the area and hit the space bar and then move it to the right and hit the space bar. After you have selected the areas, move the mouse to the Class window and type "e" to "erase" the set window "crosshairs".

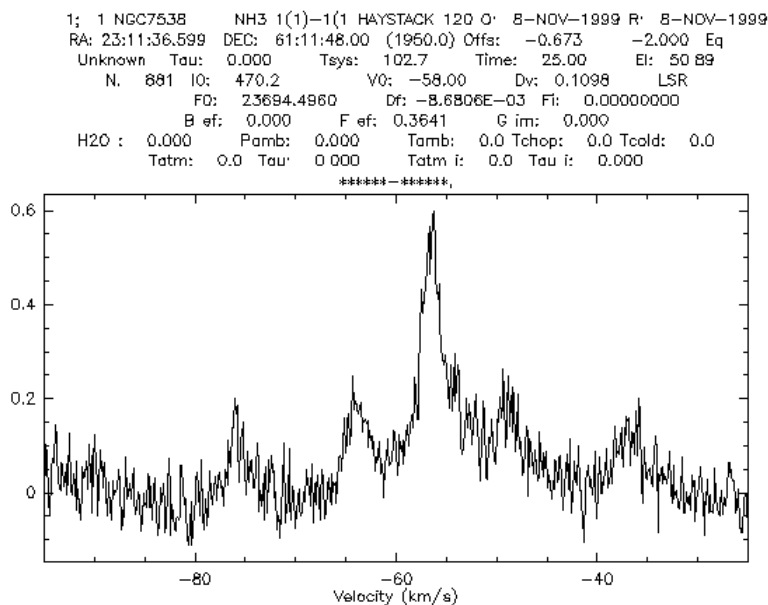
The next command will apply the baseline correction.

```
LAS> base [n]  
LAS> plot
```

Where n is the order of a polynomial - (try not to go above 3)

The corrected baseline plot might look like the following plot example. (This plot has been smoothed)

```
LAS> smooth (a couple of times)  
LAS> plot
```



As each new spectrum finishes and is converted to Class format by AutoCLASS, you will need to add that spectrum to the class.00nnn file. Go to the Class window and type:

```
LAS> new_data
```

OK, you're now ready to fit the spectral lines with a Gaussian shape. This will give you a linewidth, a line intensity, and a position of the line on the x-axis which translates to an lsr (local standard of rest) velocity. From the following three line fits, we will get an optical depth, the intensity of the central line of the (1,1), and the intensity of the (2,2) line.

For the NH3 (1,1) line you will do a two step process. The first step will give you the optical depth of the main component ($\tau(1,1,m)$) and the second step will give you the peak intensity of the main component ($T_b(1,1,m)$).

```
LAS> method nh3(1,1)
LAS> line 1
```

This will give you a cursor - go to the left and right of the middle line and hit the space bar. This will input the guesses for the first three parameters of the fit. The fourth parameter has to be entered by hand. So...

```
LAS> set cursor off
LAS> line 1          (the sample of which looks like....)
```

0 1.879 0 8.789 0 2.345 0 0 (so you type...)

```
LAS> 0 1.879 0 8.789 0 2.345 0 0.2---(you need a non-zero number here)
```

The first number of each pair of numbers in the command line above is either a 0 or a 1 - the 0 tells the fit to vary that parameter while the 1 tells it to keep it fixed.

The first pair corresponds to the area under the gaussian, the second pair gives the center velocity, the third pair gives the linewidth and the fourth pair gives the optical depth. Now you are ready to run the fit...

```
LAS> gauss
```

This will think for a bit and then give some numbers. The last set of numbers is what we need - **tau**. In order to get a printout of the fit or to save it in an ascii file, we need to save the whole spectrum in a new file. This will save the spectrum and the fit. Then we can open it as before...

```
LAS> file out nh311.fit new
LAS> write
LAS> file in nh311.fit
LAS> find
LAS> get f
LAS> plot
LAS> fit          (this will plot the fit on top of the spectrum)
LAS> print fit /outp nh311.prt (ascii file with fit)
LAS> print fit   (will print on the screen)
```

The next step is to get the peak intensity of the strongest line.

```
LAS> file in class.00nnn (reopen raw data file)
LAS> find
```

```

LAS> list
LAS> find/number n1 n2      (selects all the scans you want to average)
LAS> sum
LAS> fold                    (for frequency switched data)
LAS> plot
LAS> base n/pl              (same as before)
LAS> plot
LAS> smooth                 (the same number of times as before)
LAS> plot
LAS> set cursor on
LAS> method gauss
LAS> line 5                  (left and right of each of the five lines)
LAS> gauss

```

This will give you an area, velocity, linewidth and peak intensity for the five lines. You only need the middle one. You can save and print things out just as before in the previous section.

```

LAS> file out nh311.gaussfit new
LAS> write
LAS> file in nh311.gaussfit
LAS> find
LAS> get f
LAS> plot
LAS> fit                     (this will plot the fit on top of the spectrum)
LAS> print fit /outp nh311.gaussprt (ascii file with fit)
LAS> print fit               (will print on the screen)

```

You now want to fit a gaussian to the (2,2) line. So, open the raw data file again and select the appropriate (2,2) scans. Then you sum them again and fold as before. To give you the whole outline for completeness...

```

LAS> file in class.00nnn
LAS> find
LAS> list
LAS> find/number n3 n4      (for (2,2) scans)
LAS> sum
LAS> fold
LAS> plot

```

Now you need to set new windows for the baseline since you don't detect the hyperfines of the (2,2) line.

```

LAS> set cursor on
LAS> set window             (select the edges and the line)
LAS> base 3/pl
LAS> plot
LAS> method gauss
LAS> line 1                 (select left and right of single line)
LAS> gauss
LAS> fit

```

This will give you the fitted gaussian for the (2,2) line. So now you open a new file and write it out again..

```
LAS> file out nh322.gaussfit new
LAS> write
LAS> file in nh322.gaussfit
LAS> find
LAS> get first
LAS> print fit                (to screen)
```

or

```
LAS> print fit /outp nh322.gaussprt
```

You are all done. You have three print files with the parameters you need for the temperature calculation.

SAMPLE FIT DATA:

This is a file with the 5 components gaussian fit for the (1,1) line. The number you need is the intensity of the central component and it is underlined in the following example (it will NOT be underlined in your printout).

```
nh311-all.gfit .....
ANALYSE PRINT FIT/OUTPUT NH311-GFIT.PRT .....
23-MAR-1999 15:37:27 .....

 5   4  -.666  -1.98   .2504   1.160E-02  -76.13   7.318E-02   3.145   .160
7.480E-02  1.017E-02  1.132E-02
 5   4  -.666  -1.98   .4120   1.337E-02  -64.23   4.983E-02   3.533   .123
.110   1.017E-02  1.132E-02
 5   4  -.666  -1.98   1.411   1.480E-02  -56.80   1.904E-02   3.772   4.940E-
02  .351   1.017E-02  1.132E-02
 5   4  -.666  -1.98   .5667   1.650E-02  -49.38   5.497E-02   4.240   .167
.126   1.017E-02  1.132E-02
 5   4  -.666  -1.98   .4339   1.448E-02  -37.11   6.842E-02   4.118   .170
9.897E-02  1.017E-02  1.132E-02
```

SAMPLE OF THE METHOD NH3(1,1) FIT

The number you need to look for is called opacity and is underlined in this example.

```
nh311-all.nfit .....
ANALYSE PRINT FIT/OUTPUT NH311-NFIT.PRT .....
23-MAR-1999 15:41:15 .....
NH3 Hyperfine structure fitting .....
Area   Vlsr   Width   Opacity
 1     4   -.666  -1.98   .432   .010  -56.767   .017   3.607   .045   .442   .061   .011
.016
```

You are now ready to begin temperature calculations as outlined in the following Appendix. Your goal is to find the kinetic temperature T_K of your source.

APPENDIX -- Description of temperatures:

1. T_a = antenna temperature - the "raw" quantity measured by the radio telescope (beware - people tend to use different notation for this!). This is the temperature that is corrected for the system noise (with the system temperature measurement). It is directly correlated to the power generated at the receiver input terminals by the source.

2. To convert this antenna temperature into a "main beam brightness temperature" (T_b) we divide it by the beam efficiency. In doing so we take into account the fraction of the power that actually gets into the telescope beam. The brightness temperature is defined as the Rayleigh-Jeans temperature of an equivalent black body which will give the same power per unit area per unit frequency interval as the celestial source.

Since our source is extended we are making some assumptions here. We are assuming that the source has a constant brightness temperature across the beam and that it just fills the beam. For a more detailed explanation on how to deal with clumpy sources look at "Tools of Radio Astronomy" by Rohlfs and Wilson, p 188-196.

3. From the observed emission line several temperatures can be derived. The first value is the excitation temperature $T_{ex}(1,1)$ which describes the relative population of the (1,1) levels - i.e. the population of the parity + level to the parity - level (Fig 2 in Ho and Townes 1983, ARAA 21, 239-270).

This relationship can be mathematically expressed as:

$$N_+/N_- = g_+/g_- \exp(-h\nu/kT_{ex})$$

Here g_+ and g_- are statistical weights of the two levels - in this case they're equal and hence the ratio is 1. Now, obviously, this value T_{ex} will be different for the (1,1) and the (2,2) levels. However, one assumption that is made in Local Thermodynamic Equilibrium (LTE) is that these are equal.

4. Now, in order to calculate T_{ex} from the measured quantities, we can equate the brightness temperature to the excitation temperature as follows:

$$T_b = (J\nu(T_{ex}) - J\nu(T_{bg}))(1 - e^{-\tau})$$

Here

T_{bg} = cosmic background = 2.7K

τ = optical depth

$J\nu(T)$ is given by $(h\nu/k)/(e^{h\nu/kT} - 1)$

If we assume $h\nu/kT$ is small, then the denominator can be expanded out and $J\nu(T) = T$.

So,

$$T_b = (T_{ex} - T_{bg})(1 - e^{-\tau}).$$

And furthermore, if τ is small, then

$$T_b = (T_{ex} - T_{bg})\tau.$$

This is what CLASS is trying to give you when it does the NH₃ fit. However, since CLASS does not know what your beam efficiency is, it is really giving you a T_a . So, you have to take the CLASS number and divide by the beam efficiency to get your excitation temperature.

5. The next quantity we are interested in is the rotational temperature, T_{rot} . This temperature describes the relative population between the (1,1) and the (2,2) levels. Now, you can derive this equation by starting out with a Boltzmann equation for each level. Mangum, Wooten, and Mundy (1988, Ap.J. 388, 467-488) do this in detail - but make sure you realize - in their equations, what they call T_{ex} is actually T_{rot} .

So, finally,

$$T_{rot}(2,2;1,1) = -41.5 \left[\ln \left(\frac{-0.283 \delta\nu(2,2)/\tau(1,1,m) \delta\nu(1,1)}{e^{-\tau(1,1,m)}} \right) \ln \left(1 - \frac{T_b(2,2,m)}{T_b(1,1,m)} \right) (1 - \frac{T_b(2,2,m)}{T_b(1,1,m)}) \right]^{-1}$$

Here $T_b(1,1,m)$ and $T_b(2,2,m)$ correspond to the peak brightness temperatures of the main components of the (1,1) and (2,2) lines. The $\delta\nu$'s are the line widths of the two transitions. Everything else should be obvious.

6. The final temperature we can estimate is the kinetic temperature of the gas. This temperature is related to the velocity field in the cloud. In the case of ammonia, radiative transitions between the states we consider (called metastable states) are forbidden. So the only allowed transitions are collisional - hence the populations of the metastable levels are directly related to T_K . We can thus obtain T_K from T_{rot} (which describes the relative populations of the metastable states) using the following equation:

$$T_{rot}(2,2;1,1) \left(1 + (T_K/41.5) \ln \left[1 + (C(2,2;2,1)/C(2,2;1,1)) \right] \right) - T_K = 0$$

Here, $C(2,2;2,1)$ (use a value of $1.7 \times 10^{-11} \text{ cm}^3 \text{ s}^{-1}$) and $C(2,2;1,1)$ (use a value of $3.0 \times 10^{-11} \text{ cm}^3 \text{ s}^{-1}$) are the collision rates for a particular temperature. Its a bit circular since we have to assume a T_K to get an appropriate collision rate...but that's the way it is!

The following page contains an example of analysis questions from the lab course using Haystack Observatory taught at Boston University by the late Dr. Lynne Deutsch. Much of the Spectral Index text was originally part of the classroom/lab instructions developed by Dr. Deutsch for her students. We have used the material here with her permission and remember her for her dedication to her students and her support of undergraduate research here at Haystack.

**Boston University, questions following an astronomy class lab exercise on
Measuring the Spectral Indices of Continuum Sources**

Analysis

First answer the following questions (**show all work**), and then complete your spectral index worksheets from your observations. If you need additional space, use the back of this sheet.

- a) What wavelengths correspond to your two frequencies of observation?
- b) What is the beamsize at 22 GHz? At 43 GHz? Are they the same? Why or why not? (Give beamsizes in units of radians *and* arcseconds.)
- c) What does the constant C in equation (1) correspond to in equation (5)?

Now go to the web site <http://chandra.harvard.edu/> and follow the links to "First Chandra Images". Click on the Crab Nebula. There is a set of four images at four different wavelengths. Click on the link that says

"What do these images tell us".

Read the material on this page and answer the following questions:

1. The emission from the nebula looks quite different at different wavelengths. Why? Briefly describe how the emission is produced in each of the four observed wavelength regimes.
2. What is at the center of the Crab Nebula? How was this found?

To answer the next few questions about the history of the Crab Nebula, you will need to browse some of the links under "First Chandra Targets".

3. How bright was the supernova that produced the Crab Nebula?
4. When did the supernova actually occur? When was it first seen from Earth? Why are these times different?
5. How massive and what size is the object at the center of the nebula?

Appendix A - Sample Sourcelist File

```

# SiO Maser sources - 43122027 KHz
#
cit3.7mm      01 03 48.0   12 19 51   1950    9.5
MIRA          02 16 49.4  -03 12 13   1950   43.0
SPER.7MM     02 19 15.1   58 21 34   1950  -39.2
IKTAU.7MM    03 50 43.6   11 15 32   1950   32.0
TXCAMb.7MM   05 00 51.19  56 10 54   2000    3.76
TXCAMr.7MM   05 00 51.19  56 10 54   2000   15.7
IRC601.7MM   05 15 06.0   63 12 51   1950   50.7
ORION.7MM    05 32 46.6  -05 24 30   1950   -3.7
ORIRC2.7MM   05 32 47.0  -05 24 23   1950   -4.0
RLEOb.7MM    09 44 52.2   11 39 41   1950   -0.8
RLEOr.7MM    09 44 52.2   11 39 41   1950    4.0
VYCMA.7MM    07 20 54.7  -25 40 12   1950   23.5
SCRB.7MM     15 19 21.5   31 32 47   1950    0.0
VXSGR.7MM    18 05 03.0  -22 13 55   1950   14.0
TCEPr.7MM    21 08 52.9   68 17 12   1950    3.0
TCEPb.7MM    21 08 52.9   68 17 12   1950   -5.0
RCAS.7MM     23 58 24.781 51 23 19.1 2000   25.0
#
# H2O Maser sources - 22235080 KHz
#
W3OH.13MM    02 23 17.8   61 38 58   1950  -48.0
KLIRC2.13M   05 32 47.0  -05 24 23   1950    8.7
W49N.13MM    19 07 49.8   09 01 17   1950   10.0
W75N.13MM    20 36 50.5   42 27 01   1950   13.15
GGD37.13MM   22 54 19.2   61 45 44   1950   -9.6
GGD37blue    22 54 19.2   61 45 44   1950  -13.7
#
# Drift Map sources
#
CrabN        05 34 31.44  22 00 52   2000    0.0
cygnusA     19 59 28.36  40 44 02   2000    0.0
#
# NH3 source - 23694496 kHz
#
ngc7538     23 11 36.6   61 11 48   1950  -58.0
#
# Selected Continuum Sources
#
3c84         03 16 29.6   41 19 52   1950    0.0
3c111        04 15 02.1   37 54 29   1950    0.0
4c39.25      09 23 55.3   39 15 24   1950    0.0
3c273        12 26 33.3   02 19 42   1950    0.0
3c274        12 28 17.6   12 40 02   1950    0.0
3c279        12 53 35.9  -05 31 08   1950    0.0
3c345        16 41 17.7   39 54 11   1950    0.0
dr21         20 37 14.2   42 08 57   1950    0.0
3c454.3     22 51 29.6   15 52 54   1950    0.0

```

Appendix B - Sample Schedule File

```
# This is a basic 7mm
# SiO setup file
# 12/17/99, PAS
#
Define goSiO
  Maintenance = off
  Frequency = 43122027
  Bandwidth = 160
  Inttime = 1
  npoints = 1
  npairs = 1
  CDPmode = 1m
  Beamswitch = on
  sourcelist = point.lst
EndDefine

Define goSiO2
  Maintenance = off
  Frequency = 43122027
  setuprow=c
  Bandwidth = 160
  Inttime = 1
  npoints = 1
  npairs = 1
  CDPmode = 2m
  Beamswitch = on
  sourcelist = point.lst
EndDefine

Define Pointing
  Source = orion.7mm
  Inttime = 1
  Bandwidth = .658
  Cal
  DSS
EndDefine

Define SpectralRun17
  Inttime = 10
  Bandwidth = 17.8
  Cal
  SBS
EndDefine
```

Appendix C – Sample Setups

Listed below are sample **Umbrella** setups for receivers, focus measurements, pointing measurements and continuum and spectral-line observations. (Umbrella commands are NOT case-sensitive)

Receiver Setups

7mm (Q-Band) 35 – 49 GHz, Single Polarization, Using a Beamswitcher

Manual

Project = Chautauqua
Maintenance = Off
Frequency = 36000000
SetupRow = A
CDPMode = 1m
Npoints = 1
Npairs = 1
Bandwidth = 160
Beamswitch = On
Sourcelist = *Sourcelist Name*

Macro

Define 7mm1chsetup
Project = Chautauqua
Maintenance = Off
Frequency = 36000000
SetupRow = A
CDPMode = 1m
Npoints = 1
Npairs = 1
Bandwidth = 160
Beamswitch = On
Sourcelist = *Sourcelist Name*
EndDefine

7mm (Q-Band) 40 - 44 GHz, Dual Polarization, Using a Beamswitcher

Manual

Project = Chautauqua
Maintenance = Off
Frequency = 43122027
SetupRow = C
CDPMode = 2m
Npoints = 1
Npairs = 1
Bandwidth = 160
Beamswitch = On
Sourcelist = *Sourcelist Name*

Macro

Define 7mm2chsetup
Project = Chautauqua
Maintenance = Off
Frequency = 43122027
SetupRow = C
CDPMode = 2m
Npoints = 1
Npairs = 1
Bandwidth = 160
Beamswitch = On
Sourcelist = *Sourcelist Name*
EndDefine

13mm (K-Band) 18 - 24 GHz, Single Polarization

(Dual Polarization and Beamswitching are not available on the 13mm receiver)

Manual

Project = Chautauqua
Maintenance = Off
Frequency = 22000000
SetupRow = A
CDPMode = 1u
Npoints = 1
Npairs = 1
Bandwidth = 160
Sourcelist = *Sourcelist Name*

Macro

Define 13mmsetup
Project = Chautauqua
Maintenance = Off
Frequency = 22000000
SetupRow = A
CDPMode = 1u
Npoints = 1
Npairs = 1
Bandwidth = 160
Sourcelist = *Sourcelist Name*
EndDefine

Additional Umbrella commands for:

Pointing Observation

Bandwidth = 160
IntTime = 1
Cal
DSS

- * MHz (narrow 0.658 MHz for spectral lines)
- * 1-second data increment
- * Calibration
- * Starts an Azimuth then Elevation, 50-point scan

On then Off-source Observation

(5 minute run)

Bandwidth = 17.8
IntTime = 10
SWOffs = -1.300
Cal
SONOFF

- * MHz
- * 5-minute run (30 seconds x 10)
- * Off-Source RA offset = $\text{IntTime} \times -0.125 + -0.050$
- * Calibration
- * Moves to Offset position for 5 minutes and then repeats the scan when the source arrives at the scan starting position

Frequency Switched Observation

(5 minute run)

Bandwidth = 17.8
FrequencySwitch = On
FreqsOffs = -4450 4450 4450
IntTime = 10
Cal
SFS

- * MHz
- * Offsets based on Observing Bandwidth
- * 5-minute run (30 seconds x 10)
- * Calibration
- * Starts a 5-minute frequency switch observation

Appendix D – Useful Scripts

Following are listed some of the shell scripts used to produce plots and other information. The list is not complete but will include the most useful to the student observer. These scripts are resident on the pointing computer and are accessed at any system xterm prompt.

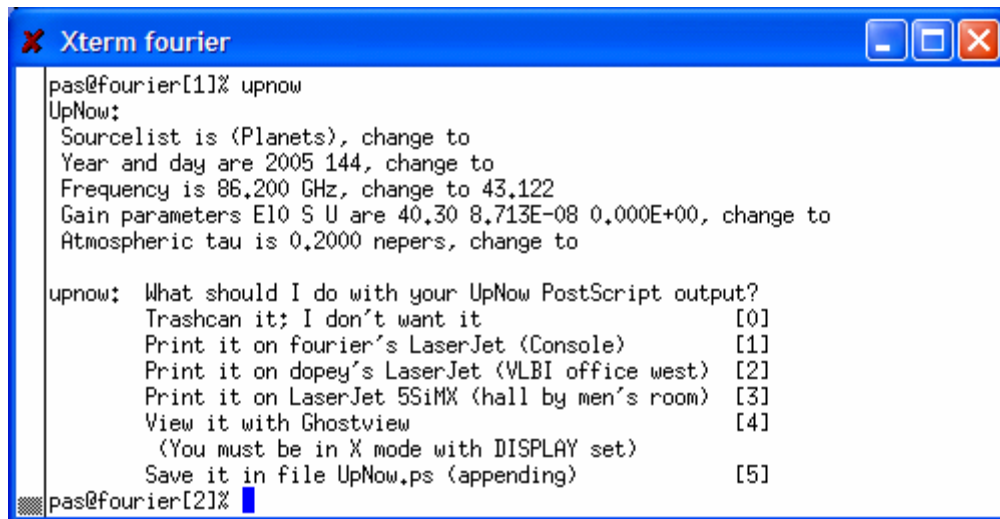
Upnow

This script reads the observer's sourcelist and produces a plot of the source rise and set time and optimum observing time for a selected frequency. Optimum observing times are based on the properties of the telescope and the atmosphere at a given frequency.

Syntax:

```
chautauqua@fourier% upnow
```

Then follow the instructions on the screen. You will be asked to toggle or change the Sourcelist, the day and year, the frequency, the gain parameters and the atmospheric tau. The gain and atmospheric settings are not usually changed from the default. The user will then be asked to designate where the output should go. The output file is in PostScript format (seen on next page).

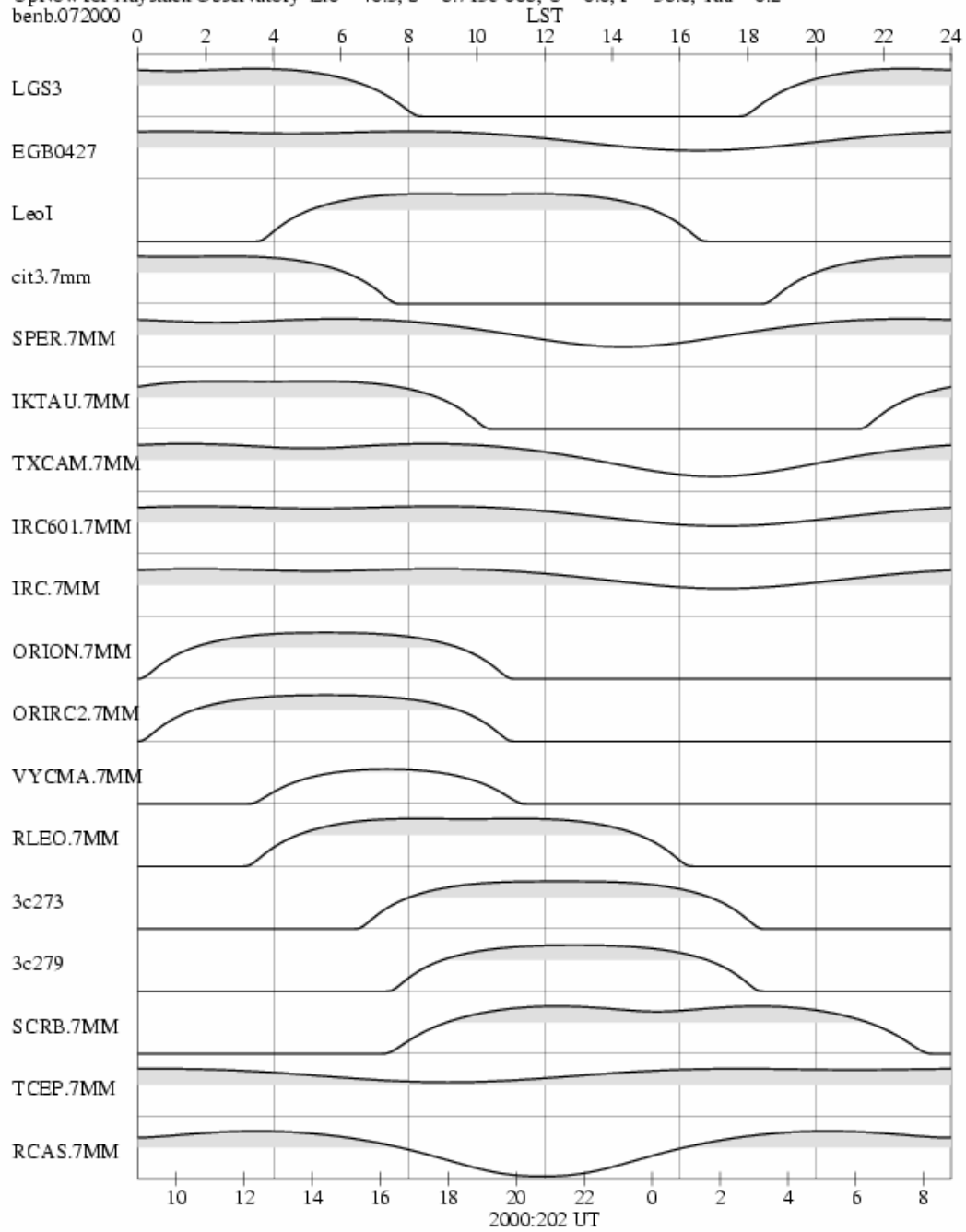


```
Xterm fourier
pas@fourier[1]# upnow
UpNow:
Sourcelist is (Planets), change to
Year and day are 2005 144, change to
Frequency is 86.200 GHz, change to 43.122
Gain parameters E10 S U are 40.30 8.713E-08 0.000E+00, change to
Atmospheric tau is 0.2000 nepers, change to

upnow: What should I do with your UpNow PostScript output?
Trashcan it; I don't want it [0]
Print it on fourier's LaserJet (Console) [1]
Print it on dopey's LaserJet (VLBI office west) [2]
Print it on LaserJet 5SiMX (hall by men's room) [3]
View it with Ghostview [4]
  (You must be in X mode with DISPLAY set)
Save it in file UpNow.ps (appending) [5]

pas@fourier[2]#
```

UpNow for Haystack Observatory EIO = 40.3, S = 8.713e-008, U = 0.0, F = 38.0, Tau = 0.2
benb.072000



Index

This script will produce a listing of the spectra produce for any selected day and year (provided the data has not been archived to storage disks or DAT tapes). The information in the list includes the file number of each spectrum, the Project name (user provided during observing setup), the Source name, the T(sys) of the observation, the Elevation of the source above the horizon, the Universal Time of the observation, the Line-Rest Frequency and the observing bandwidth.

This information defaults to the screen but can be piped to a printer or a file using standard Unix commands.

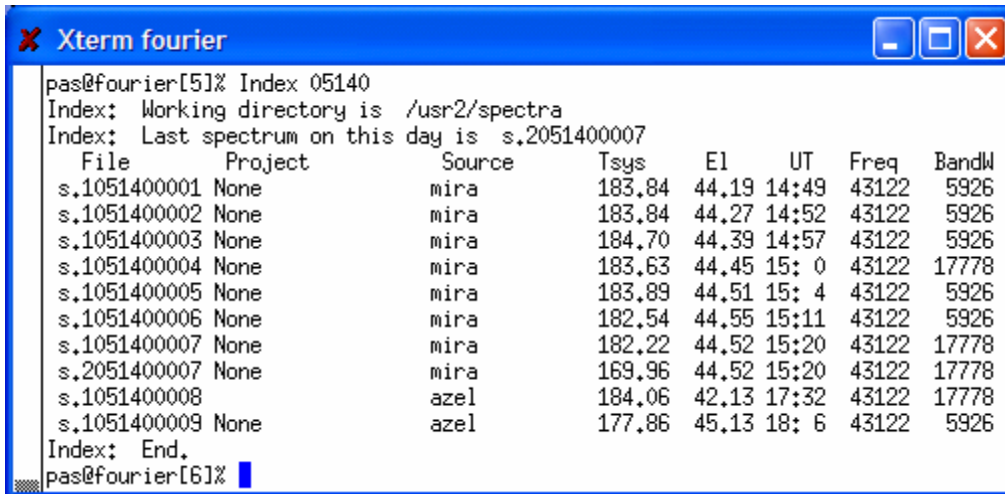
Syntax:

chautauqua@fourier% **Index yyddd nnnn nnnn** (the default nnnn is all will be listed)

where, yy = year

ddd = UT day number

nnnn = the range of spectra file numbers the user wishes to list



```
pas@fourier[5]% Index 05140
Index: Working directory is /usr2/spectra
Index: Last spectrum on this day is s.2051400007
  File      Project      Source      Tsys      El      UT      Freq      BandW
s.1051400001 None        mira        183.84    44.19  14:49  43122    5926
s.1051400002 None        mira        183.84    44.27  14:52  43122    5926
s.1051400003 None        mira        184.70    44.39  14:57  43122    5926
s.1051400004 None        mira        183.63    44.45  15: 0  43122    17778
s.1051400005 None        mira        183.89    44.51  15: 4  43122    5926
s.1051400006 None        mira        182.54    44.55  15:11  43122    5926
s.1051400007 None        mira        182.22    44.52  15:20  43122    17778
s.2051400007 None        mira        169.96    44.52  15:20  43122    17778
s.1051400008          azel        184.06    42.13  17:32  43122    17778
s.1051400009 None        azel        177.86    45.13  18: 6  43122    5926
Index: End.
pas@fourier[6]%
```