NAIC/NRAO Single Dish Summer School
Hands-On Project

HI Emission in Extended Galaxies

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Contents

CHECKLIST

Before beginning observations for this project, you should:

- Read this document and (at the least) skim through the appendices
- Have discussed, and come to a consensus, with your group as to what your source(s) and calibrators will be
- Have discussed, and come to a consensus, with your group as to what your correlator set-up will be
- Have a reasonable idea of what will you need to do to complete your observations
- Know what time you are expected to begin, and fully understand how you are getting from your lodgings to the observing room.
- Bring this write-up, your list of sources, something to write with, and paper to the observing session

1. Introduction

This project is designed to demonstrate the fundamentals of spectral line observing. We will observe galaxies at HI (in emission). All four of the galaxies have HI known to extend to distances comparable to, or beyond, the Arecibo beam. The results of these observations will then be compared to GBT data of the same four galaxies (taken in advance but reduced by you). Beam maps will also be made with the Arecibo telescope in order to both provide beam sizes and to calibrate the Arecibo data.

This project is designed to demonstrate the fundamentals of spectral line observing and the restrictions due to beam sizes, sidelobes, etc. All spectral line observations will be made with the position switching technique. Position switching is the technique of observing first the position of interest and then a blank sky (off-source) observation. The blank sky observation is used to remove atmospheric and systematic telescope noise, and a position should be picked for the blank sky observations so that the same part of the dish (the same AZ and Zea) is used for both observations. At Arecibo this is especially important as standing waves are a large problem at Arecibo due to the unique geometry of the Gregorian system which allows for considerable reflection from sources inside and outside the telescope beam.

2. The Sources

The sources for this observing were chosen in advance. All sources had the following requirements:

- First, the sources had to be accessible to the Arecibo dish (the 'Arecibo sky') during your observations. A reasonable estimate for the length for the length of time an object will be in the Arecibo sky can be obtained from the following: A source at Arecibo latitude (18.3° declination) takes approximately 3 hours to transit the Arecibo sky, while a source 17° from the telescope latitude has only about 20–30 minutes while it transits the dish. Sources more than $\sim 18^\circ$ from the AO latitude will never be visible to the AO system.
- Second, the sources needed to be bright enough to be readily detected by Arecibo and the GBT. This means a minimum peak density of $\sim$10-20 mJy.
- Third, there could not be any RFI (Radio Frequency Interference) at the frequency at which the source lies. The easiest means for finding out this information at Arecibo is though the "Spectrum Management" web page at *http://www.naic.edu*. At the GBT that information can be found at *http://www.gb.nrao.edu/~glangsto/rfi/lband*.

3. Front-End

For this project you will be using the L-band (1-2 GHz) receivers. Details on the two receivers used given in Table 1.

4. Backend Set-up

You need to decide the both the correlator set-up and the filter(s) you desire for your Arecibo observations. For the correlator, you simply need to decide what resolution(s) and sampling level(s) you want for your observations. Note that since you have four individual boards to play with, you have considerable freedom in this regard. The available range in bandwidths is 50.0 – 0.781 MHz. Bandwidth is only available as a binary fraction of 50.0MHz. That is, you can choose from 50.0, 25.0, 12.5, 6.25, 3.125, 1.562, 0.781, or 0.195 MHz.

The filter chosen should be wide enough to insure your data gets through, but no wider than necessary. The L-narrow has a 1130MHz - 1530MHz bandpass filter which was installed around 15 May, 2002. Additionally, you now have the option of selecting either a 1280MHz high-pass filter or a 1370MHz high-pass filter to use in conjunction with the bandpass filter (or you can choose to use the bandpass filter only).

Additionally, you should decide whether or not you need to use the "radar blanker". The radar blanker serves to "blank" data acquisition by the correlator during pulse emission by the FAA radars at 1330 and 1350 MHz situated on Pico del Este, PR. The blanking can be extended for a duration longer than the basic radar pulse in order to also eliminate delayed reflections of the pulse from aircraft, etc. The blanker adds approximately 10% to the amount of time needed for a given observation.

The GBT observations were all taken with: two banks (boards, in Arecibo nomenclature), one polarization/bank, 12.5 MHz bandwidth/bank, 8196 channels/bank, 9-level sampling.

Table 1. Details of the L-band Receivers Used

	Arecibo	**GBT**
Name and Number:	L-Narrow (lb, lbn, 6)	1.15 – 1.73 (1 – 2 GHz)
Frequency Coverage:	1.28 – 1.50 GHz	1.15 – 1.73 GHz
Measured Sensitivity:	8-11 K/Jy	$\sim$3 K/Jy
Measured System Temp:	26–30 K	20 K
Native Polarization:	Dual circular	Linear
Beam Size (at 1415 MHz):	3.1 x 3.5 arcmin	$\sim$9 arcmin

5. Blank Sky Observation

The unique geometry of the Arecibo system allows for considerable reflection from sources both inside and outside the beam. Additionally, the imperfect shape of the Arecibo dish and irregularity of the surrounding countryside results in a telescope gain which varies across the dish. As a result, the blank sky (off-source) observations taken in a typical position switching sequence at Arecibo are not 'randomly' chosen blank sky positions. Instead we force the off source observation to trace the same pattern across the dish as the on source observation. As the telescope is given one full minute between the on and off source observations (to allow the telescope to slew to the correct position), a five minute on source observation will have its off source observation taken at the same declination but at an RA position which is six minutes (in time) later than that of the source. In this way the same azimuth and zenith angle positions are traced for both the on and off source observations.

Potential Problems: The off source observation is supposed to be a blank sky observation. This means you need to be sure the sky area which will be used for this observation does not contain any significant continuum sources or any other galaxies. If continuum, or another galaxy, is present at the location of your off source observation, you need to reconsider your observing strategy (i.e. choose another source or choose a different integration time). A great resource for determining the location on continuum near your object is the Northern VLA Sky Survey (NVSS), available online through *http://www.cv.nrao.edu/~jcondon/nvss.html* (For the purpose of this project the postage stamp server is good tool.) To search an area of sky for other galaxies, the NASA Extra-galactic Database (NED) at *http://nedwww.ipac.caltech.edu* has a "near position" search that is very complete.

All GBT observations were taken with a the off source observation lying at a ΔRA = -87 arcmin.

6. System Temperature

Receiver temperatures at both telescopes are obtained through observations of noise diodes with known (pre-measured) temperatures. At Arecibo, the telescope is typically left at the off-source (blank sky) position and a 10 second observation is done with the diode on, and then 10s with the diode off. To insure that these measurements accurately reflect the system temperature at the time of the source observation, the noise diode (or cal) measurements are usually done at the end of each on+off source observation. The L-Narrow receiver at Arecibo has only one noise diode available to it – a low voltage, correlated (between polarizations) diode. The most recently measured values for this diode are given in Table 2.

At the GBT the diode is typically continuously fired in a 'winking' fashion, firing every 0.5s during observations. The on and off cal measurements must then be extracted from the on and off source observations. The GBT L-band receiver also has only one diode, which can be set to either a low or high voltage. When the observations are done in the 'winking' mode (as yours were), the low voltage diode (low cal) is typically used. The most recently measured values for this diode are given in Table 3.

7. Telescope Gain

Like all astronomical observations, one of the most important steps in spectral line observing is converting your observations from local units (e.g. a local temperature) into universal units. For HI observations a typical unit of measurement is the Jansky (Jy). Janskies are units of flux density, with 1 Jy = 10^{-23} ergs cm^{-2} s^{-1} Hz^{-1}. Conversion from measured source temperatures (what you have, after taking T_{sys} into account) into Janskies (what you want), is done through observing a number of sources with well established fluxes, and then determining a conversion between measured temperature and flux density. This conversion factor is known as the telescope gain. (Technically, telescope gain is simply the telescope response to a point source. Here, we express the gain in terms on antenna temperature due to a point source of flux density 1Jy which lies in the center of the beam. With this definition, then, the gain is in units of K/Jy).

A good calibration source is a point source with a strong, non variable flux. For L-band observations (the regime in which HI observations are done), this means you want a source which is considerably smaller than the size of the beam ($3.6'$ for Arecibo, $9'$ for the GBT) size of the beam. Additionally, the flux should be at least 20-30 mJy but not larger than a few Janskies (or 100Jy at the GBT), or you will exceed the dynamic range of the telescope. A list of possible flux calibrators is given in Appendix I.

At Arecibo you use neither all of the dish, nor identical parts of the dish for every observation. Additionally, the Arecibo dish (like most things in reality) is not perfect – the dish, as used, is not 100% spherical, there are cables and supports to hold the Gregorian and receivers in place, etc. As a result the gain at Arecibo has a dependence both on azimuth and zenith angle. The ideal calibrator at Arecibo would be a good calibrator (as defined above) which lies only a few beam widths away in declination, and at the same RA, from the source in which you are interested. An observer would then perform a number of observations on source in which they are interested and then observe the calibrator source, repeating this sequence throughout the night.

Unfortunately, reality is rarely nice enough to grant every object in the Arecibo sky its own calibrator source. (Or perhaps fortunately, since otherwise the sky would be too filled with strong continuum sources to perform any decent spectral line observations.) To accommodate this fact, and to save telescope time by avoiding each observer needing to repeat the same observations, each observing band at Arecibo has a 'gain curve' – a two-dimensional fit of the telescope gain versus azimuth and zenith angle. Ideally, this curve would be applied directly to the observed data to obtain flux densities in Jy. Like with any experiment, though, blind trust in the absolute values of a standard curve could readily land an observer into trouble. Instead it is usually a very good idea to observe a few good calibration sources located near (in azimuth and declination) to where your object will be located. These observations can then be used to confirm (or if necessary

Table 2. Arecibo LBN Noise Diode Temperatures - Measured 28 Jan 01

Freq	Pol A [K]	Pol B [K]	Error	Freq	Pol A [K]	Pol B [K]	Error
1200	2.51	2.53	5%	1360	1.78	1.86	5%
1220	2.07	2.11	5%	1380	1.84	1.90	5%
1240	1.80	1.86	5%	1400	1.89	1.94	10%
1260	1.65	1.74	5%	1420	1.94	1.97	10%
1280	1.60	1.70	5%	1440	2.00	2.02	10%
1300	1.61	1.72	5%	1460	2.08	2.11	10%
1320	1.65	1.76	5%	1480	2.19	2.27	5%
1340	1.71	1.81	5%	1500	2.39	2.53	5%

Table 3. GBT L-band Low-Voltage Noise Diode Temperatures in the Frequencies of Interest

Freq	Pol X [K]	Pol Y [K]	Freq	Pol X [K]	Pol Y [K]
1.34	1.59	1.61	1.384	1.52	1.67
1.344	1.57	1.5	1.388	1.54	1.66
1.348	1.54	1.56	1.392	1.52	1.64
1.352	1.55	1.53	1.396	1.6	1.65
1.356	1.5	1.53	1.4	1.58	1.6
1.36	1.52	1.55	1.404	1.58	1.63
1.364	1.49	1.55	1.408	1.55	1.7
1.368	1.47	1.58	1.412	1.56	1.6
1.372	1.51	1.61	1.416	1.59	1.66
1.376	1.52	1.59	1.42	1.6	1.62
1.38	1.57	1.58	1.424	1.66	1.72

correct) the standard calibration curves, and should be repeated periodically throughout your observing run. (Copies of the curves can be found through the web pages of the respective receivers – *http://www.naic.edu/menuimag/astronomy.htm.*)

The GBT's unblocked aperture makes it less important (at L-band) that you obtain a calibrator near your source of interest than that you get a reliable calibration source. Consequently, only one calibrator was looked at with the GBT, using the same position switched observing method as the source observations. In this case, you need merely to account for any changes in the atmospheric opacity between where your observations were taken and where your source is. The equation for change in gain due to atmospheric opacity is simply $e^{-\tau/sin(EL)}$ where EL is the object's elevation and τ is the atmospheric opacity. Using frequency (f) in GHz, the formula to find τ is

$$\tau = 0.01061 - 1.1434\times10^{-5}\mathrm{f} + 0.000439\mathrm{f}^2 - 2.727\times10^{-5}\mathrm{f}^3 + 7.628\times10^{-7}\mathrm{f}^4 - 8.0153\times10^{-9}\mathrm{f}^5$$

8. Putting it all together – Data Calibration

Once all your observations have been taken, its time to sit down in IDL analyze your data. A description of the commands and methods for IDL is given in appendix. Rather than bog you down with various commands, this section is designed to give an overview of the steps necessary to turn your data into measurements of gas mass, velocity, etc. A more detailed description of the calibration steps is included in 'Notes Relevant to Spectral-Line Calibration" by C. Salter, which is included in this hand-out.

The first step in your data reduction is to remove the background noise from your data. For position switching, this is done using the off source observations taken during your observing run. Removing background noise from your source involves subtracting out the contributions due to the receiver, extraneous noise from the ground due to spillover, vignetting, etc, atmospheric noise, and background radiation (e.g. the galactic background emission and the Cosmic Background Radiation). Conveniently, all of this is readily done by simply subtracting your of source observation from your on source observation.

At this point your data is simply in units of accumulated antenna temperature. To apply your calibration corrections you need to convert it into independent units – in this case, percentage of system temperature. As you already have a blank sky observation taken for the same length of time, this conversion is done by dividing your data by your off source observation.

The next step is to convert your data from $\%\mathrm{T}_{sys}$ into units of absolute temperature. To accomplish this, you need to determine the system temperature using your observations of the standard noise diodes (cals). Following the same logic as for your source, and knowing the absolute temperature for the observed noise diode (T_{CAL}), the noise diodes can be used to determine the system temperature via

$$\mathrm{T_{SYS}} = \mathrm{T_{CAL}} \times \left[\frac{\mathrm{CAL_{ON}} - \mathrm{CAL_{OFF}}}{\mathrm{CAL_{OFF}}}\right]$$

The antenna temperature of your source is then

$$\mathrm{T}_{\mathrm{SOURCE}} = \mathrm{T}_{\mathrm{SYS}} \times \left[\frac{\mathrm{ON} - \mathrm{OFF}}{\mathrm{OFF}}\right] = \mathrm{T}_{\mathrm{CAL}} \times \left[\frac{\mathrm{CAL}_{\mathrm{ON}} - \mathrm{CAL}_{\mathrm{OFF}}}{\mathrm{CAL}_{\mathrm{OFF}}}\right] \times \left[\frac{\mathrm{ON} - \mathrm{OFF}}{\mathrm{OFF}}\right]$$

As a last step you should convert your measured source temperature into units of Janskies by applying the relevant gain curve. Remembering that the gain is in units of K/Jy, the final equation is then

$$\mathrm{Signal(Jy/beam)} = \frac{\mathrm{T}_{\mathrm{CAL}}}{\mathrm{G(za,az)}} \times \left[\frac{\mathrm{CAL}_{\mathrm{ON}} - \mathrm{CAL}_{\mathrm{OFF}}}{\mathrm{CAL}_{\mathrm{OFF}}}\right] \times \left[\frac{\mathrm{ON} - \mathrm{OFF}}{\mathrm{OFF}}\right]$$

Remember that the GBT data has a "winking" cal, while the Arecibo data does not. This must be considered when determining your system temperature.

9. Converting your Data into Useful Numbers

Once you've successfully calibrated your data, you need to turn your spectra into useful (publishable) facts – HI mass, velocity widths, etc. Fortunately, this step is extremely easy. Using your favorite data reduction software, you need to (a) sum all the relevant data (if you haven't already); (b) perform a baseline subtraction on your data; (c) integrate the total flux of the galaxy (to obtain the flux and, ultimately, the total HI gas mass), and (d) fit Gaussian(s) to your spectra to obtain the central velocity and the FWHM at 50% and 20% of the Gaussians (that is, obtain the velocity widths).

9.1. Baseline Subtraction:

The region chosen for your baseline subtraction should be large enough that sufficient channels are available to get a reasonable fit, yet small enough that the baseline you are fitting will be accurate for the spectral line in which you are interested. Typically, at Arecibo, this means no more than a few hundred channels on either side of the spectral line, and sometimes much less (depending, of course, on the width of the observed line). The other factor to consider when fitting a baseline is that you do not want to over- or under-compensate for the true baseline. The interim correlator at Arecibo (the one which you are using) is extremely good, for many reasons, including the fact that it gives remarkably flat baselines. As a result, assuming you choose a baseline which is limited to the region reasonably near your observed line, the baseline which you fit to your data should not be of order larger than two.

9.2. Determining $\mathbf{v}_{HEL}$, $\mathbf{w}_{20}$, $\mathbf{w}_{50}$

Converting your frequency array to velocity in the earth's (AO) standard of rest is straight forward using the standard frequency/velocity equation (given in Appendix F). However, that is not the standard of rest desired in most instances. Instead, you should (in this case) convert velocities from the earth (topocentric) standard of rest to the heliocentric (sun-centered) standard of rest. To do this, you need to know the topocentric to heliocentric correction for your object at the time you observed it. This can be gotten from the Astronomical Almanac. To save time, though, you can also obtain this information in two ways:

- **Arecibo**: The Arecibo data have the heliocentric correction in the data header. In IDL, this means just typing the following command (assuming your data lie in the variable b) print,b.b1.h.dop.velobspro. This number should be subtracted from your velocities.
- **GB**: For the GBT, you can determine the heliocentric velocity correction needed for a given source at a given time by first logging into a solaris machine and then running the program "doppler". More specifically, type the following:
  ```
  slogin arcturus
  doppler
  ```
  After running the program, be sure to type `exit` to logout of the arcturus machine.

Velocity widths (w_{20} & w_{50}) are simply the velocity widths of your line at 20% and 50% of the peak velocities, respectively. These should be found directly from your data.

9.3. Determining the HI mass:

First, as already mentioned, you need to use you favorite data reduction program to integrate and obtain the total flux of your source. When performing this integration, you want to be sure that your y-axis (or intensity) is in units of Janskies, and your x-axis is in terms of velocity. The flux you obtain will then be in the very useful units of Jy km s^{-1}. This can be converted to, i.e.total gas mass (in units of $M_\odot$) through the conversion:

$$M(HI) \;=\; 2.356\times 10^5 \;\times\; \left[D(Mpc)^2\right] \;\times\; \int (Jy\; km\; s^{-1})\;\; M_\odot$$

where $\int$ is the measured flux of your source and D is the distance to your object in Mpc (for distant objects – objects where v_{sys} is considerable larger than v_{random} – a reasonable distance estimate is D=v(km s^{-1})/H_0(km s^{-1} Mpc^{-1})).

9.4. When no line is seen (setting upper limits):

If no line is detected during your observation, it is still useful to obtain an upper limit to the flux density of your object.

In order to set flux limits you first need to decide on what a likely velocity width (v_{20}) for your object is. The easiest means to do this is to go to the literature and determine common velocity widths for similar objects. When choosing the velocity width to assume for your (undetected) source, remember that you are setting *upper* limits on the flux and mass. This means that you should not choose a small velocity width simply because it gives an impressively low flux limit. Instead, if anything, you should err on the side of overestimating your object's velocity width.

Once you've decided on a reasonable velocity width, you can determine your flux, and mass, upper limits. There are two common methods for setting these limits. In the first method, you need only to determine the r.m.s. noise of the region in your spectra which should contain the line of interest. Your flux upper limit would then be $< \# \sigma > \times \sigma_{rms} \times v_{20}$, where $< \# \sigma >$ represents the signal-to-noise level, in number of σ_{rms}, at which you would expect to see your spectral line. (This is typically of order 3 or higher.) You can now convert that flux upper limit to a mass limit via the conversion equation given earlier.

The other common method for determining upper flux limits for non-detections at Arecibo is by integrating the noise over the region where your source should lie. This gives you a 1σ upper limit to you flux. If there is any non-linear components to your baseline, this method will provide a more realistic (albeit higher) flux limit.

One final note in this discussion is the possibility that you do not know the exact red shift of your source. If you know an approximate velocity, or a range, you can apply either of the above techniques repeatedly across the velocity range of interest, and then use the highest value as your flux upper limit. If, though, you have no idea what the red shift of your source is, you are probably best off just reporting your r.m.s. values.

10. Extended Emission

The last issue which should be addressed with your Arecibo data is the relation and shape of the beam compared with the distribution of HI gas in your observed galaxies. You can obtain the beam shape through taking a cross or "spider" scan on a strong calibrator source during your observations. This is done automatically when you run Arecibo's calibration procedure. Using your derived beam shape, and knowing both the optical size and morphology of the galaxies you studied, and assuming a gas distribution within the galaxy, you can then estimate the total gas the galaxy actually has (as opposed to the amount you measured).

One viable method would be to make a model of the HI gas and use the beam map you obtained to actually determine the total HI content. A standard alternative method for determining the correction for the source-to-beam size ratio is based off the idea that the HI distribution is an elliptical Gaussian and that the beam is circular. The correction for the source-to-beam size ratio is then given by

$$\mathrm{f_c} = \left\{1 + \left(\frac{\mathrm{a_{HI}}}{\theta}\right)^2\right\}^{1/2} \left\{1 + \left(\frac{\mathrm{b_{HI}}}{\theta}\right)^2\right\}^{1/2}$$

Here, θ is the half-power beam with of the telescope, a_{HI} and b_{HI} are the half-power major- and minor-axis diameters of the neutral gas distribution, and all quantities are expressed in units of arcminutes (Staveley-Smith, L., Davies, R. D., & Kinman, T. D. 1992, MNRAS, 258, 334 and Thuan, T. X., & Martin, G. E. 1981, ApJ, 247, 823).

In both of the above cases you must still make an estimate of the total distribution of HI gas within a galaxy. The most common method for making this correction is by using the galaxy's morphological type to determine a HI-to-optical diameter ratio. Two plots are attached at the end of this hand-out showing different determinations of the HI-to-optical diameter ratio versus. morphological type.

One final issue which needs to be considered is that of the beam sidelobes. That is, you must make an estimate as to whether or not your object will lie within the sidelobes of the Arecibo beam. If you determine the object will, then you need to determine (using much the same reasoning as you did for the main beam) what percentage of the total gas of the galaxy came in through the sidelobes.

APPENDICES

Table A. Possible HI Emission Sources

Object Name	**RA** (B1950)	**Dec** (B1950)	$\mathbf{v}_{rad}$ (km/s)	**Type**	$\mathbf{D}_{opt}$	$\mathbf{D}_{HI}$
UGC 11651	20:55:04.9	25:46:17	1525	Sdm	3.1'	6'
UGC 11707	21:12:20.2	26:31:36	905	SAdm	3.6'	7'
NGC 07013	21:01:26.6	29:41:54	779	SA(r)0/a	4.0'	5'
UGC 12281	22:56:43.3	13:36:24	2568	Sd	3.44'	7'

Table B. List of Potential Flux Calibrators

Name	**RA** (B1950)	**Dec** (B1950)	**Flux (1420)** (Jy)	**Size**	**Variable?**
B0300+162	03 00 26.9	16 15 04	2.73	$<10''$	N
B0316+162	03 16 09.1	16 17 41	7.79	$<10''$	N
B0333+321	03 33 22.4	32 08 36	3.35	$<10''$	Y
B0428+205	04 28 06.86	20 31 09.2	3.86	$<10''$	N
B0453+227	04 53 42.17	22 44 41.7	3.21	$<10''$	N
B0500+019	05 00 45.18	01 58 54.7	2.30	$<10''$	N
B0518+165	05 18 16.53	16 35 26.8	8.09	$<10''$	N
B0521+281	05 21 14.4	28 09 50	1.77	$\sim2.1'$	N
B0640+233	06 40 04.9	23 22 10	2.64	$<10''$	N
B0711+356	07 11 05.62	35 39 52.5	1.83	$<10''$	Y
B2041+170	20 41 59.4	17 00 00	0.66	$<10''$	N
B2153+377	21 53 45.52	37 46 13.9	6.81	$<10''$	N
B2209+080	22 09 32.2	08 04 25	1.69	$<10''$	N
B2210+016	22 10 05.17	01 37 59.4	2.84	$<10''$	N
B2223+210	22 23 14.8	21 02 50	1.97	$<10''$	Y
B2247+140	22 47 56.33	14 03 56.7	2.13	$<10''$	N
B2249+185	22 49 07.7	18 32 44	1.72	$<10''$	N
B2251+158	22 51 29.5	15 52 54	13.2	$<10''$	Y
B2314+038	23 14 02.27	03 48 55.2	4.51	$<10''$	N
B2338+132	23 38 00.9	13 16 23	1.78	$<10''$	N

Table C. GBT Observations and Files

Source	Observation	Files	EL	UT
B2223+210	Off	data_9_*	52.6376	2003-07-07 10:01:51
B2223+210	On	data_10_*	52.6376	2003-07-07 10:07:13
B2247+140	Off	data_19_*	58.2073	2003-07-07 11:27:10
B2247+140	On	data_20_*	58.2073	2003-07-07 11:32:36
UGC 11651	Off	data_263_*	62.8586	2003-06-23 13:59:21
UGC 1165	On	data_264_*	62.8586	2003-06-23 14:02:43
UGC 11707	Off	data_265_*	65.0674	2003-06-23 14:06:58
UGC 11707	On	data_266_*	65.0674	2003-06-23 14:10:21
NGC 07013	Off	data_267_*	62.9451	2003-06-23 14:15:15
NGC 07013	On	data_268_*	62.9451	2003-06-23 14:18:36
UGC 12281	Off	data_269_*	65.0021	2003-06-23 14:25:09
UGC 12281	On	data_270_*	65.0021	2003-06-23 14:25:09

Note. —
1. All data is in the GBT_obs directory in your data reduction area.
2. All GBT galaxy observations were taken with 10s dumps for a total of 3 minutes on and off source.
3. All GBT calibrator observations were taken with 10s dumps for a total of 5 minutes on and off source.
4. Noise diodes were turned on and off at five second intervals.

D. Data Reduction Commands

While the data from Arecibo can be converted into a variety of formats, the data reduction for this project will take place within IDL. Your idl 'environment' (which tells IDL where to look for its various files) has already been set. Below are a number of useful commands to analyze you data.

General IDL commands:

- `idl` : starts idl
- `file = 'data_266_25.txt'` : defines the variable file to be equal to the string 'data_266_25.txt
- `openr,lun,file,/get_file` : Opens a file (defined be the variable "file") for read-only access, assigning that file to the variable "lun".
- `data=make_array(3,8192)` : Defines the variable data to be a 3x8192 array
- `readf,lun,data` : reads the contents of the file assigned to the variable "lun" into "data".
- `close,lun` : Closes the file assigned to the variable "lun"
- `free_lun,lun` : Frees the variable "lun" so that it can be reassigned.
- `hor` (`ver`): lets the plot's horizontal (vertical) axis be automatically defined based off the min and max values in the plotted data.
- `hor,x,y` (`ver,x,y`): Sets the plots horizontal (vertical) axis to be between x and y
- `plot,x,y` : Plots the arrays x and y
- `plot,data[1,*],data[0,*]` : Plots the 2nd and 1st columns from the array data
- `min(x)` (`max(x)`)) : Finds the min (max) value of the x array
- `result=total(data[1,*])` : Sums the elements of the column 1 in data
- `print,result` : prints the value of the variable "result"
- `?` (`?command`) : opens the help window (to the desired command)
- `set_plot, 'PS'` : Sets the plot type to postscript
- `device, /encapsulated` : Sets the device output to encapsulated postscript
- `device, /inches, xsize=11, ysize=8.5` : Sets the size of the output file
- `device, filename='plot.ps'` : Sets the name of the output file (if output is not to screen)
- `device,/close` : Closes the output device
- `set_plot,'X'` : Sets the plot output to the x-windows display

Arecibo Specific Commands:

Folks are Arecibo have put considerable effort in to writing a number of Arecibo-specific commands for data reduction. These commands are all documented on the Arecibo web pages (http://www.naic.edu/∼astro/data/data_formats/idl/index.shtml), but below are the commands you will most likely find useful.

- `corlist,lun` : List the contents, with a brief header, of the data in the file associated with variable lun
- `stat=corget(lun,b,scan=scannumber)` : get the first data dump of scan "scannumber" and assign it to variable b
- `corplot,b` : Plot the data in variable b. The options here include
  - vel = plot against velocity (the default is frequency)
  - m=0 - 8 = plot one or more boards. 0 = all boards, 1 = 1st board, 2 = 2nd board, 3 = boards 1 & 2, 4 = board 3, 5 = boards 1 & 3, 6 = boards 2 & 3, 7 = boards 1, 2, & 3, 8 = board 4.
- `cornext,lun,b` : Input to variable b, and then plot, the next data dump in the file
- `stat=corposonoff(lun,b,scan=219200075)` : Do an (on-off)/off calculation for each on+off data dump, average the results, and output it to variable b.
- `stat=corimgonoff(lun,scannumber)` : Make a time vs. frequency plot of all the data in the on and off spectra, starting with scan number "scannumber". Then, over plot the (on-off)/off spectra.
- `bcor=corgain(b)` : Apply the standard gain correction to the data in variable b, output the results to the variable bcor
- `stat=gainget(az,za,freq,rcvrNum,gainVal)` : Find the gain value from the standard curves for a given azimuth, zenith angle, frequency (in MHz), receiver (=6 for the L-narrow). Output the results in the "gainVal" array
- `bavg=coravg(bcor,/pol)` : Average the polarizations for the data in variable bcor and output the results to the variable bavg
- `spectr=test(bavg)` : Do a baseline fitting to the data and then find the area under the curve for the data in bavg. Output the resultant data to the variable "spectr". (Be sure to follow the instructions on the screen when you do this.) This output from this command will be the following:
  - Area (flux), central velocity, and width at 50% of the mean flux.
  - Area (flux), central velocity, and width at 20% of the mean flux.
  - Area (flux), central velocity, and width at 50% of the peak flux.
  - Area (flux), central velocity, and width at 20% of the peak flux.

The Arecibo data is written into what is called a structure of arrays. This means that if you wish to work only with the data (and thereby bypass the above AO-specific routines), you need to access the data from the data arrays. This could be done with a series of commands along the lines of:

```
data=make_array(2,2048)
data[0,*]=b.b1.d
data[1,*]b.b2.d
```

GBT Specific Commands:

There are no commands in idl specific to GBT data processing. Instead, I have made a sample script showing an (incomplete) data reduction session for the GBT. This script is shown below and is also available in your data reduction area. The file name is "script". Note that in IDL you can copy (using the left mouse button) and paste (using the right mouse button) a number of lines of code into the command window at any time.

Both the GBT data and the idl script live in your project area in the directory "GBT_obs".

```
;
;Creating an array from all the off-source scans of UGC 11651
;
off=make_array(36,3,8192, /double)
data=make_array(3,8192, /double)
for j=0,35 do begin &$
  file='data_263_'+strtrim(string(j+1),1)+'.dat' &$
  openr,lun,file,/get_lun &$
  readf,lun,data &$
  off[j,*,*]=data &$
  close,lun &$
  free_lun,lun &$
endfor
;
;Creating an array from all the on-source scans of UGC 11651
;
on=make_array(36,3,8192, /double)
data=make_array(3,8192, /double)
for j=0,35 do begin &$
  file='data_264_'+strtrim(string(j+1),1)+'.dat' &$
  openr,lun,file,/get_lun &$
  readf,lun,data &$
  on[j,*,*]=data &$
  close,lun &$
  free_lun,lun &$
endfor
;
```

```
;Making a median filtered array from the individual on and off source dump
;
on_av = make_array(3,8192,/double)
off_av = make_array(3,8192,/double)
for i=0,2 do begin &$
 for j=0,8191 do begin &$
  on_av[i,j] = median(on[*,i,j]) &$
  off_av[i,j]=median(off[*,i,j]) &$
 endfor &$
endfor
;
;Making an (on-off)/off array
;
onoff = on_av
onoff[1,*] = (on_av[1,*] - off_av[1,*]) / off_av[1,*]
onoff[2,*] = (on_av[2,*] - off_av[2,*]) / off_av[2,*]
;
;Smoothing data by 15 channels
;
onoff_smo=onoff
onoff_smo[1,*]=smooth(onoff[1,*],15)
;
;Plotting versus frequency
;
plot,onoff[0,*],onoff_smo[1,*]
;
;Determining the topocentric velocity
;
vel=make_array(8192,/double)
vel = 299792458 * ( 1420.4058 - onoff[0,*]/1.000000000E6 ) / 1420.4058
vel = vel / 1.000E3
;
;Send nice plot of data vs. velocity to a postscript file
;
!p.thick=4
!p.charsize=2.0
!x.thick=3
!y.thick=3
set_plot, 'ps'
device, /inches, xsize=11, ysize=8.5
device, bits_per_pixel=8, /encapsulated, /color, filename='plot.ps'
```

```
plot,vel,onoff_smo[1,*], xtitle="velocity [km/s]",ytitle="Intensity [Dumb units]"
device,/close
set_plot,'X'
```

Appendix E.

Spectral-Line Observing at Arecibo Observatory

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March 20, 2002

For help/questions/comments/suggestions on this document, please contact Karen O'Neil (*koneil@naic.edu*)

E. Spectral-Line Observing at AO

E.1. Introduction to Spectral Line Observing at AO

Before you begin your observations, and probably even before you submit your proposal, you need to consider the possible telescope parameters and observing procedures available at Arecibo. This involves deciding which receiver you wish to use, the observing procedure and parameters you wish to employ, what frequency range and set-up for the correlator boards you want, integration length, any equipment you may need to deal with RFI (filters, radar blankers, etc.), etc.

In most circumstances, all of these choices can be made in advance of your observing run through running the AO-Control graphical users interface (gui) off-line, and then saving your set-up files under an appropriate name. These files are automatically saved into your project area on the "observer" computer. (This assumes your project area already exits. If it does not, you should talk to your Friend of the Telescope.)

Note – Your project area is accessible from any Arecibo computer, and is at /share/obs4/usr/aXXXX, where aXXXX is your project number. If you do not have a project area, but still wish to use the gui, you may enter "a9999" as your project number. If you do this, though, you should be aware that the set-up file you create will not be accessible to your actual project. The "a9999" project is for testing purposes only.

A discussion of the above decisions is given in the following sections.

E.2. Receiver Choice

The majority of the receivers at Arecibo are housed in the new Gregorian Dome. The exceptions are the 47-MHz and 430CH receivers attached to the old Carriage House. As these receivers are not commonly used for spectral line work they will not be discussed here. Detailed information on the Carriage House receivers can be found both on the relevant receivers' web page and in the pulsar observing handbook.

The available Gregorian receivers are listed in Table D. In most cases, only one receiver will be available which will meet your frequency requirements. (REMEMBER – At present only one receiver can be used at a time.) In a few cases, such as in the L and S bands, more than one receiver may be available which suit your needs. In these cases, you probably want to choose the receiver with the narrowest frequency range which fits your need. Alternatively, you may wish to choose the most sensitive (lowest SEFD – system equivalent flux density) receiver. Conveniently, these two choices often lead to the same receiver (i.e. using the L-narrow over the L-wide, when possible). The most up-to-date information on the receivers can be found on the Arecibo web pages at http://www.naic.edu/~astro/RXstatus/.

L-Wide Receiver Options: If you choose to use the L-wide receiver, a number of options not available to the other receivers must be decided. In particular, you must choose your polarization type and r.f. filter.

- Polarization type: The L-wide receiver is a native linear receiver. It can be converted to circular polarization by selecting a quadrature hybrid inserted outside the dewar.
- Filter bank: Bandpass filters available for the L-wide receiver are not adjustable. This means that when you use a filter, **be sure it covers the frequency range which you will be observing,** and not your rest frequencies. L-wide filter options are: 1120-1220, 1230-1470, 1550-1820, 1100-1800, 1360-1470, 1180-1280 MHz, or no filter at all. Note that more than one filter can be selected at a time, but you should not use filters which overlap in frequency as that will cause ripples in your baseline.

NOTE: A smaller filter bank will soon be available for both the **L-Narrow** and **S-Wide** receivers as well.

E.3. Observing Procedures

The readily available observing procedures, and those we **strongly** encourage observers to use, are the procedures available with the observing gui. It should be noted that it is, of course, possible to run procedures not covered by the gui. If you choose to do this, though, you should be aware of two things. First – you MUST inform your Friend of the Telescope (FoT) well in advance, so he or she has the opportunity to make sure you will be able to observe in the manner you wish. Second – you MUST be aware that since you are observing using a non-standard procedure, the software may not exist to aid you in your data reduction, and the overworked computer department at Arecibo is under no obligation to write software for you. You will therefore have to pick your favorite data reduction package (one which supports one of the many formats in which Arecibo data can be written – see the information available at http://www.naic.edu/~astro/misc for more on this), and write your own data reduction routines.

The procedures available on the gui (as of March 02) are:

E.3.1. **Standard On**

This routine is designed to read in the current correlator set-up, go to the chosen source, and then take data pointing directly at the source. This routine will automatically wait until you are on source before beginning to take data. A Doppler correction can be applied to your observations either at the beginning of each scan or only at the beginning of the first scan, depending on your choice. Additionally, this routine allows you to take an ON/OFF calibration pair (one 10s scan with the noise diode on, followed by a 10s scan with the diode off), using the chosen noise diode configuration (see Section E.6). The other choices for this routine are the duration of the scan, the record dump time, and the number of "loops" or scans to take. Details, and options, for the Doppler correction routine are given in Section E.8.

E.3.2. **Run Correlator**

This procedure is similar to the 'Standard On' routine *except that it completely ignores your source list* and acquires data wherever the telescope is pointing. This means that no Doppler corrections are applied, and the correlator begins taking data as soon as the "Observe!" button is pushed. The only adjustable parameters are the record dump time, scan duration, number of scans, frequency, and correlator board set-up. The downstairs power levels should be adjusted for this routine.

The "Run Correlator" procedure is typically only used for telescope and RFI diagnostics.

E.3.3. **Cross Scan**

This procedure uses the correlator to perform a cross scan on your chosen source. The only three options you have for this procedure is the number of loops (i.e. the number of complete cross scan patterns you wish to be performed), the cross scan pattern – either the 'standard' cross (+) pattern which does one azimuth and one zenith scan, or a 'spider' ($\ast$) pattern which consists of four scans, each separated in position angle by 45°, the starting offset of each scan (with the default set to be 3 times the half-power beam width of the telescope for that receiver). Data is currently sampled in this procedure every second, at a rate of 60 times per strip. **This means that you MUST be careful not to over drive the telescope**, a concern which is especially important for the lower frequencies and near zenith.

E.3.4. ON/OFF (Position Switching)

This is the standard procedure for basic spectral line observations at Arecibo. The procedure simply observes ON your source for x minutes and then takes a 'blank sky' observation OFF your source for the same amount of time and tracking the same azimuth and zenith angle range. This is followed by recording your chosen noise diode configuration ON for 10s and OFF for 10s. This procedure will provide the simplest means to eliminate the standing waves in your baselines. These standing waves are due to the unique geometry of the Arecibo Gregorian system which allows for considerable reflection from sources inside and outside the beam.

Your choices with this procedure are:

- Scan duration (for the ON-source observation) – You can set this to any integral number of minutes, up to 20. Choosing a large integration time, though, is not necessarily beneficial. First, the greater the integration time the better the chance that there will be a slight change in system temperature, system gain, etc. between your ON and OFF-source observations. Second, as you need to track the same range of azimuth and zenith angles for your ON and OFF scans, your slew time between the ON and OFF observations increases as your observation time increases (see "wait time" below). Typically, observing times are kept to within 5 minutes (with 5 minutes as the most efficient, and therefore default, choice). If you wish to observe for more than 5 minutes at a time, please carefully consider your project, slew rates, etc.

- Wait time – This is the length of time (in minutes) the data-taking system waits while the telescope slews (and then settles) between acquiring the ON and OFF-source data. Again, this must be an integer. If your scans are for 5 minutes or less, your wait time should be set to 1 minute (the default setting). For longer observations
you need to increase your wait time (particularly near zenith). Your total observation time is:
$$2\times(\text{scan duration}) + (\text{slew time}) + (\text{calibration time})$$
A 5 minute ON/OFF + 10s CAL takes $\sim$11.3 minutes. A 7 minute ON/OFF, (which has a 2 minute slew time plus a cal) takes 16.3 minutes.

- Number of Loops in a Sequence – This sets the total number of ON/OFF + CAL cycles to be taken on each object each time the "Observe" button is pushed. The default setting is for one loop (one ON+OFF+CAL-ON+CAL-OFF cycle).

- Adjust power – This setting allows you to adjust the correlator power levels. The options are: never, before the first ON/OFF+CAL pair only, or before every ON/OFF+CAL pair. The default setting is for the power to be adjusted before every ON/OFF+CAL pair.

- Doppler update – This allows the observer to choose when the Doppler update is applied – either at the start of every ON/OFF+CAL pair, or only at the beginning of the entire observing sequence. The default setting is for the Doppler to be updated at the beginning of each ON/OFF+CAL pair.

Doppler correction options are described in Section E.8, and the noise diode configuration options are described in Section E.6.

E.3.5. **Drift Map**

This is the optimum mapping routine (in terms of giving the flattest baselines) for the Arecibo/Gregorian system. The intent of the routine is for the user to map an area slightly larger than the area in which he/she is interested. Baseline subtraction then occurs via fitting a baseline between the opposite ends of each scan (Figure 1).

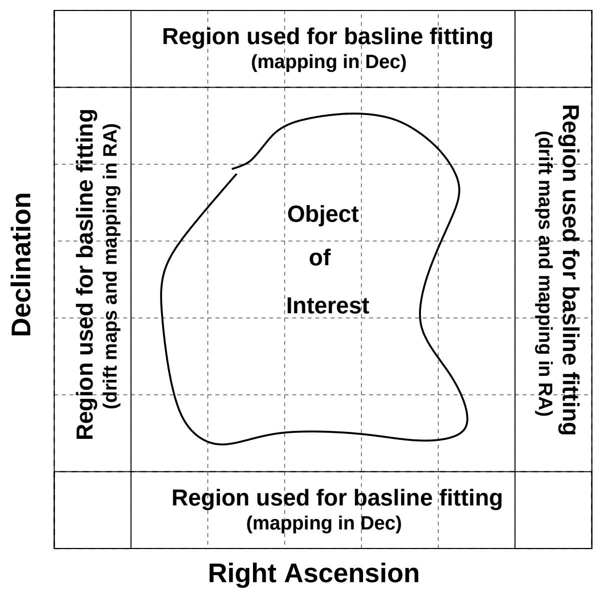

Fig. 1.— *Example showing 'typical' mapping techniques for baseline removal.*

A number of decisions have to be made when running this routine:

- **Number of Strips:** This is the total number of strips to be covered for the map. The map size (in declination), is then (Number of strips − 1) × (Dec step) + (Beam size). If you wish to do a complete map, you must have (Number of strips) = 2×INT[(Dec Offset)/(Dec Step)+0.5] +1
- **Time per strip:** This is the "drift duration" for each strip (in seconds), and it sets the map size in the RA direction. For computing this time, just note that the sky will drift by

at 15 arcseconds/sidereal seconds. There are 1.0027379 sidereal seconds per solar second.

Each strip ill be centered such that its center will be the RA given by your source list, while the center of the central strip will be centered on your listed Declination.

- **RA Offset time:** This procedure differentiates between solar and sidereal seconds. The integration times of the correlator, and drift times for the strip are measured in solar (or UTC) seconds. The 1-second ticks from our atomic clock drive this. Setting this option to "solar" will give a slightly funny RA offset, but the routine will do a better job than the "sidereal" setting in aligning the map relative to the correlator integrations (as long as driftTime is exactly divisible by corRecSecs).

  Note that the zenith angle position of the telescope for each strip is set by the starting RA ([object RA] + [RA Scan Length]/2) and the current LST.

- **Dec Offset:** This is the starting offset from the map center for the declination strips, in arcminutes. A complete map is then 2×(Dec offset) wide. If you wish to do a complete map, you must have (Number of strips) = 2×INT[(Dec Offset)/(Dec Step)+0.5] +1 the declination of your first strip will be ([object Dec] + [Dec Offset]).
- **Dec Step:** This is the amount by which the declination is stepped at the end of a strip in arcmin (or series of strips, if the number of strips per step is larger than one). If you wish to do a complete map, you must have (Number of strips) = 2×INT[(Dec Offset)/(Dec Step)+0.5] +1
- **Strips per Step:** This setting allows you to integrate multiple strips before stepping in declination.
- **Doppler Update;** This setting allows you to update the Doppler parameters either once at the beginning of your map or at the beginning of each strip.
- **Cal & Cal Time:** These are simply the noise diode options described in Section E.6, with the additional option of setting the integration time for the calibration scan. The noise diodes are fired at the end of each strip.
- **Settle time:** This setting tells the routine to delay for an extra x seconds at the start of each strip before taking data. This gives any oscillations in the azimuth arm extra time to settle down.
- **Doppler Correction:** This is described in Section E.8.

E.3.6. RA/Dec & Dec/RA maps

These maps allow you to drive the telescope in RA or Dec while stepping in Dec or RA, respectively. When using these routines, you must carefully consider what method you will use for baseline subtraction. The unique geometry of the Arecibo system produces a wide variety of standing waves in a typical baseline. These waves change shape considerably as the telescope is moved in azimuth and zenith angle. As a result, baseline stability offered by drift scans is considerably better than when the maps are made by driving the telescope. This means that if you can make your desired map using the drift map routine, then, although it will take longer, it is in your best interest to do so.

Many of the options available for these procedures are the same as for the drift map routine, which is described above. The differences are:

- **First Strip:** This option allows you to pick up a map in the middle, instead of forcing a full map coverage each time. Here you would enter the number of the strip at which you wish to begin observing.
- **RA (Dec) Offset & Strip Time:** These parameters not only define the size of your map in the RA (Dec) direction in arcmin, but also, when combined with the strip time, set the drive rate on the sky; i.e., the RA drive rate is set to 2×60×(RA offset)/(Strip time) [in arcsec/sec]. The type of arcsecond (little circle or great circle) is set by the RA offset type (see below), or a Dec drive rate of 2×60×(Dec offset)/(Strip time) for the Dec/RA map option.

  You should adjust the correlator dump time to sample the data at whatever rate you want (normally less than or equal to half a beam), where faster sampling can allow for better RFI reduction, but the over sampling can result in extemely large data files.
- **Dec (RA) Offset & Dec (RA) Step:** These options set the map size (in arcmin) in the Dec (RA) direction to be 2×(Dec Offset) (or 2×(RA Offset) if you are driving the telescope in the declination direction). Additionally, when combined with the Dec (RA) Step option, these options set the number of strips in each map to be (Number of Strips) = 2×INT[(Dec offset)/(Dec Step)+0.5] + 1 (or (Number of Strips)= 2×INT[(RA offset)/(RA Step)+0.5] + 1 for maps driving in Dec). If you only want one strip centered on the Dec (RA) listed in your source list, you should set the Dec (RA) step size and offset to zero.
- **Drive Direction:** This option specifies whether you wish to drive the telescope, taking data alternating in direction between scans, or only in one direction. The second option is more time consuming as the telescope must slew across the mapped region before beginning the next strip.
- **RA Offsets in great/little circles:** This option allows you to set whether the RA offsets are in great or little circles of arc. (Recall that a little circle is the standard astronomical definition for RA. Great circle will cover 1/cos(Dec) greater length on the sky.)

E.3.7. **Frequency Switching**

Although is it technically feasible to observe in frequency-switching mode at Arecibo, we do NOT support frequency-switching at the moment. This is due to the (so far) unpredictable nature of the standing waves in the data, which makes frequency-switched data essentially useless. The possibility of using Arecibo in frequency switching mode is still being investigated, and hopefully it will someday become an option.

E.3.8. **Calibration Scans on Continuum Sources**

As with any type of observing, it is always a good idea to run a few calibration scans at the beginning of, and during, your observing run to make sure that the telescope and receiver are behaving properly. At Arecibo this is done by performing a "spider scan" (a pattern of four scans across an object, each separated in position angle by 45°) on a standard calibration source. The output of this scan is automatically displayed on the screen, allowing the observer to asses the current state of the telescope and chosen receiver.

Continuum sources in the list used for flux density calibration were selected in an ad-hoc fashion from a variety of places, but primarily from Kuehr et al (A&AS, 45, 367, 1981), the compendium of linearly polarized sources by Tabara & Inoue (A&AS, 39, 379, 1980), and an unpublished list of unconfused calibrator sources prepared from the NVSS survey by Jim Condon and Qi Feng Yin. For each source, all reliable flux density measurements from both the literature and web-available catalogs have been fitted against frequency using the following spectral form:

$$\log_{10}(\mathrm{S(Jy)}) \;=\; \mathrm{a0} \;+\; \mathrm{a1} * [\log_{10}(\mathrm{freq(MHz)})] \;+\; \mathrm{a2} * (\exp(-\,[\log_{10}(\mathrm{freq(MHz)})])$$

The values for the constants are given in the displayed source list after the word "flux:". All sources in the catalog listed as 'good' sources are believed to be non-variable. Additionally, if the source size is not given, it is believed to be less than about $15''$. It should be noted, however, that: (a) some of the sources in this catalog are significantly linearly polarized. If you wish to calibrate on a polarized source, you should determine in advance which source(s) are appropriately polarized sources; (b) We cannot guarantee that all sources are excellent calibrators at all frequencies. For example, you should bear confusion and source-size considerations in mind when selecting a calibrator source at any frequency. It is therefore highly recommended that you observe a few different calibrators. (And if you do find a source to be a poor calibrator at a given frequency, please tell us about it, via the "gui comment" button.)

The frequencies at which the standard spider-scan calibration is done is set by the receiver chosen. Note that when running the calibration button you cannot change the board center frequencies, bandwidths, or scan length. The scan length is set to be six times the half-power beam width, and the center frequencies and bandwidth are listed as Table E.

A typical output from a standard spider-scan calibration is shown in Figure 5. This information is obtained by running Carl Heiles' Mueller Matrix routines on the data to correct for instrumental polarization (described fully in Heiles, et.al. 2001 PASP, preprint, and also available as AOTM 2000-05, available at http://www.naic.edu/∼astro/aotms/performance.htm. The output is as follows:

- **First Line:** Source name, date, and starting scan number
- **Second Line:** Receiver name, board number, and center frequency (in MHz)
- **Third Line:** Azimuth and zenith angle pointing errors, in arcsec, for the A and B polarizations
- **Fourth Line:** System and source temperatures
- **Fifth Line:** Percent by which the source is linearly polarized; Position Angle of the polarization vector (North through East)
- **Sixth Line:** Percent by which the source is measured to be circularly polarized
- **Seventh Line:** The half-power beam width in the azimuth and zenith angle directions (in $'$)
- **Eight Line:** Coma intensity and position angle
- **Ninth Line:** Telescope gain, in K/Jy, determined using the source flux density at the observing frequency
- **Tenth Line:** Efficiency for the Main Beam + First Sidelobe

Note that the data which results from the "calibrate" button goes into a different file than all other data taken with the gui. That is, rather than going into a file named "corfile.$<$ *today's date* $>$. $<$ *proj* $>$. $<$ *incremental number* $>$", it goes into a files named "**calfile**.$<$ *today's date* $>$. $<$ *proj* $>$. $<$ *incremental number* $>$".

E.4. Correlator Boards

There are four *independent* correlator boards available in the correlator spectrometer. Each board can be assigned any available bandwidth, center frequency, sampling level, polarization, and number of channels. Note though that for purposes of Doppler correction the boards can only be configured to work as four independent boards or as one joined system. That is, two boards

Table D: Gregorian Receivers

Frequency Range	**Receiver Name**	**Native Pol.**	**Sensitivity (K/Jy)**	**System Temp (K)**
0.312 - 0.342	327	Dual Linear	5-6	160
0.425 - 0.435	430	Dual Circular		55
0.609 - 0.614	610	Dual Linear	8	130
1.12 - 1.73	L-wide	Dual Linear	8-11	35-40
1.28 - 1.50	L-narrow	Dual Circular†	08-10	25-30
1 .8 - 3.1	S-low	Dual Linear	7	40
2.33 - 2.43	S-Radar	Dual Circular	9-10	25-30
3.85-6.00	C	Dual Circular	4-8	32-34
8.0 - 10.0	X	Dual Circular	1.5-3*	43.48*

†The L-narrow is circularly polarized only at 1420MHz
and becomes increasingly elliptically polarized away from this frequency.
*Receiver still being calibrated. These numbers are very preliminary.

Table E: Calibration Frequencies for Standard Spider Scans

		Center Frequencies/Bandwidth [MHz]			
Receiver	**HPBW**	**Board 0**	**Board 1**	**Board 2**	**Board 4**
327	15′	326/25	326/1.563	326/0.781	
430	12′	430/25	430/12.5	429/6.25	431/6.25
430CH	10.′	430.0/12.5	430.0/1.563	430.0/3.125	
610	8.0′	612.0/6.25	612.0/1.563	609.75/0.781	613.25/0.781
lbn	3.4′	1300/25	1375/25	1415/25	1500/25
lbw	3.4′	1175/25	1300/25	1375/25	1415/25
lbw	3.4′	1415/25	1550/25	1666/25	1610/25
sbn	2.2′	2380/25			
sbw	2.2′	2212/25	2380/25	2690/25	2850/25
cb	1.0′	4500/25	4860/25	5000/25	5400/25
xb	0.58′	8500/25	8800/25	9000/25	9200/25

cannot be overlapped and centered on one frequency while the other two are set to another frequency (Figure 2).

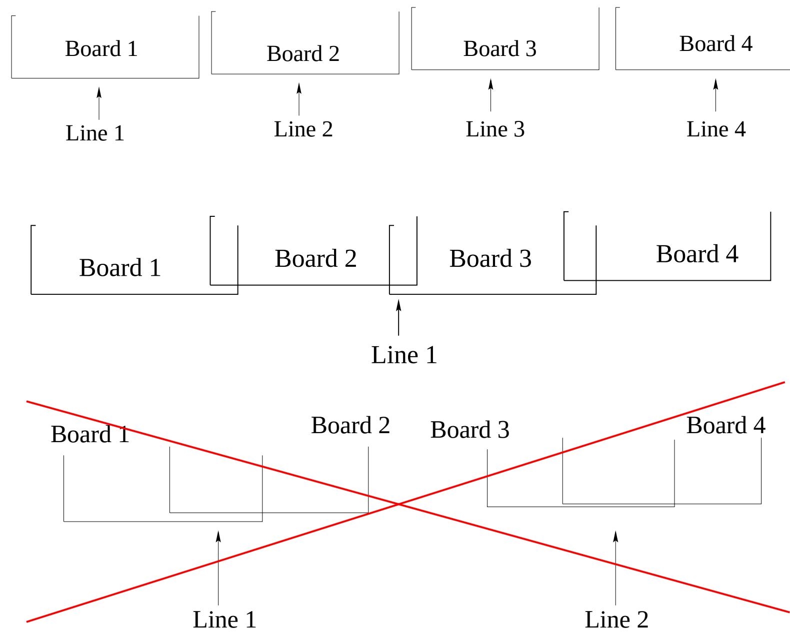

Fig. 2.— *The top two images show the possible configurations of the correlator boards – acting as four independent boards and acting together, respectively, while the bottom panel exemplifies an observing strategy not allowed with the current system.*

The options are detailed below:

- **Center Frequency:** This is the frequency on which the individual board is centered. This can either be the rest frequency or observed frequency of your lines. (A description is given below of the possible velocity corrections which can be made to the entered frequencies.)

- **Bandwidth:** The available range in bandwidths is 50.0 – 0.781 MHz. Bandwidth is only available as a binary fraction of 50.0MHz. That is, you can choose from 50.0, 25.0, 12.5, 6.25, 3.125, 1.562, 0.781, or 0.195 MHz.

- **Sampling level:** Your data can be sampled with either 3-level, 3-level interleaved, or 9-level sampling. 9-level operation achieves 98% of the signal-to-noise of analog correlation, whereas 3-level sampling achieves 81%. One advantage of 9-level sampling is to limit the effects of RFI (usually) to just a few channels. **You cannot use 9-level sampling with a 50-MHz bandpass.** If you wish to use the 50-MHz bandpass you must use 3-level interleaved sampling.

- **Polarization:** For each board you have the option of having either A, B, A & B, or full Stokes polarizations. If you use either only A or only B polarization and 3-level interleaved sampling, you can have access to the entire 4096 channels on each board. If you choose to split a board into both A & B polarizations, or increase the sampling levels, you naturally cut down on the the number of available channels.

- **No. of Channels (Lags) Used:** The total number of channels available on each board is 4096. This number can only be used, though, if you are using 3-level (interleaved) sampling. Increasing your sampling to 9-level cuts the total number of channels available in half (to 2048). A complete listing of the options is given in Table F. Note that the smaller your number of channels, the smaller (in size) your data file will be for a given record dump. Your options for the number of channels to use are: 4096 (only with one polarization and 3-level interleaved sampling), 2048 (available for the 3-level A and B polarization set-up or the 9-level sampling with one polarization), 1024 (available for all set-ups), 512, 256, 126, 64, 32, or 16 channels.

E.5. Integration Time (per Data Record)

This is the indivisible time interval after which your data is regularly dumped to the disk. On the gui it is the

(correaltor dump time) * (number of cycles per integration)

The smaller you make this number (albeit you aren't allowed to go below 1ms) the larger your data file will be. So, if you are in a RFI-free frequency range, you may want to set your integration time to as much as 60s. However, if you are in a zone often affected by RFI, you may want to set this to be a much smaller values, say, 1s.

Table F: Possible Correlator Configurations

Sampling	**Max BW per sbc**	**Pol/sbc**	**lags/sbc**	**Resolution at 1420MHz**
9-level	25MHz	1	2048	2.6 km/s
9-level	25MHz	2	1024	5.2 km/s
3-level	25MHz	2	2048	2.6 km/s
3-level interleaved	50MHz	1	4096	2.6 km/s
3-level interleaved	50MHz	2	2048	5.2 km/s
3-level Stokes	25MHz	–	2048	2.6 km/s

E.6. Noise Diode Configuration

This chooses which noise diode configuration you wish to use when calling the "cal" commands. One of the high cals is often a good choice, although if you are unsure of which diode to use you should consult with your Friend of the Telescope. Additionally, it should be noted that not all receivers have the choice of all configurations. If you choose a noise diode configuration which is not available for a given receiver, your request will be ignored and you will instead end up with the default setting for that receiver. The list of choices is given below, and the availability is listed in Table G.

Description:
nocal: run no calibration scans. This saves time but is rarely a good idea
lcal: low uncorrelated cal. diodes A,B straight through (D1→Pol A, D2→Pol B)
hcal: high uncorrelated cal. diodes A,B straight through (D1→Pol A, D2→Pol B)
lxcal: low uncorrelated cal. diodes A,B with crossover (D2→Pol A, D1→Pol B)
hxcal: high uncorrelated cal. diodes A,B with crossover (D2→Pol A, D1→Pol B)
l90cal: low correlated cal with 90 deg phase shift (D2+90°→Pol A, D2→Pol B)
h90cal: high correlated cal with 90 deg phase shift (D2+90°→Pol A, D2→Pol B)
lcorcal: low correlated cal with 0 deg phase shift (D1→Pol A, D1→Pol B)
hcorcal: high correlated cal with 0 deg phase shift (D1→Pol A, D1→Pol B)
Here, D1 is noise diode 1 and D2 is noise diode 2. The diode values can be found both in the telescope control room (ask the operator on duty for the book) or on the web sites of the individual receivers.

E.7. The Radar Blanker

The radar blanker serves to "blank" data acquisition by the correlator during pulse emission by the FAA radars at 1330 and 1350 MHz situated on Pico del Este, PR. The blanking can be extended for a duration longer than the basic radar pulse in order to also eliminate delayed reflections of the pulse from aircraft, etc.

The blanker itself is situated in the "receiver room" (the room next to the Control Room itself), and is to be found in Rack 3, Box 1-10; i.e. just below the spectrum analyzer. The device should be permanently locked to the FAA radar pulses; to confirm this check the blanker box, where the "out of lock" light should not be lit, and the "FAA Radar On" light should be glowing green. If this is not the case, please report it immediately via a GUI comment, the telescope operator or, for immediate action if during working hours, to Edgar Castro, Jon Hagen or Bill Sisk of the Electronics Department. The blanker box also has a knob which is used to set the blanking duration. This has settings between 100 and 750 microsec; the typical value used is 400 microsec.

Note that the switch found beneath the meter on the left of the box should be in the "acquired signal level" position. A "black belt" user can display the signals from the "detected output" and "blanking pulse" connectors to the right of the box on the digital scope to check the alignment of the blanking pulse with the FAA radar signal. (Alternatively, you can ask the operator if he/she is able to connect the oscilloscope for you.)

In the GUI, the button to switch ON or OFF the radar blanker is found at the bottom left of the "spectral line observer's widget" (see Fig. 9). When you click this ON, an information box will query you as to what is happening. The blanker will remain selected and operating until you switch it off by clicking on the same button. The equivalent instructions that could be entered directly into the vx-works line of the main AO_Control GUI window are "corblank on" and "corblank off"; note that if you use these vx-works commands directly in this way, the status displayed of the GUI blanker button of the "spectral line observer's widget" will change accordingly. (But why bother with direct vxworks commands when a click on the GUI will do the same for you!)

E.8. Standards of Rest & Redshift Corrections

You need to decide which standard of rest you would like to use. The options are: None, Heliocentric, Geocentric, Topocentric or LSR. You also need to decide how you want this correction to be applied - to the center of each correlator board or to the four boards as a whole (thereby preserving the topocentric frequency offset between the boards). Typically, this choice depends on whether each board is centered on a known spectral line, or if you are doing a search in velocity space for an object. If you have centered each board onto a spectral line, then you likely want the boards to have their velocity corrections determined individually. If you are doing a search, in which case you want the relative spacings of your boards to remain the same, then you should have the velocity correction applied to the center of your boards. (In this case you would choose the spectral line for which you are searching. See Section E.10 for more information.)

The last decision you need to make in this section is what velocity/redshift system you would like to use in your source list. Currently the options are: velocity(optical), velocity(radio), and z(optically determined redshift). A thorough discussion of these options can be found in Chris Salter's "Notes Relevant to Spectral Line Calibration" which can be found at http://www.naic.edu/~astro/misc.

E.9. The Source List

This is the list of objects you wish to observe. Ideally, it should be named 'src.list' and should be placed in your project area on the data-taking computer.

The format for your source list is:
name RhRmRs.s DdDmDs.s b/j velocity # Any comments you have

Name:	Your object name, usually given as one word (no spaces). If you really wish to use spaces in your names, put them in quotes.
RhRmRs.s:	The hours, minutes, and seconds in RA of your object
DdDmDs.s:	The declination degrees, minutes, and seconds of your object. This can be preceded by a + or −.
b/j:	The epoch of your coordinates (b=B1950, j=J2000). You can have both epochs within your list.
v:	The velocity of your object. This can be in km/s or in redshift (optical or radio definition)
# Comments:	These will show up in the gui windows

An Example source list looks like this:

K2314_095B	231647.0	+094845	b	0.	#Good target
"IRAS 23161"	231841.7	+095202	j	0.	#Good Target
PGC071141	232044.6	+094735	j	0.	#Possible
IRAD23196	232210.7	+070003	j	0.	#Good Target
AGC331652	232328.4	+094438	b	10.	#Lousy Target
AGC331653	232349.0	+094440	b	3333	#Good Target
NP09_0606	232443.0	+094942	b	4135	#Lousy Target
CGCG406_100	232450.0	+093130	j	0.	#Lousy Target
CGCG406_032	231449.6	090322	j	0.	#Observe every night!

An Example source list looks like this:

K2314_095B	231647.0	+094845	b	0.	#Good target
"IRAS 23161"	231841.7	+095202	j	0.	#Good Target
PGC071141	232044.6	+094735	j	0.	#Possible

IRAD23196	232210.7	+070003	j	0.	#Good Target
AGC331652	232328.4	+094438	b	10.	#Lousy Target
AGC331653	232349.0	+094440	b	3333	#Good Target
NP09_0606	232443.0	+094942	b	4135	#Lousy Target
CGCG406_100	232450.0	+093130	j	0.	#Lousy Target
CGCG406_032	231449.6	090322	j	0.	#Observe every night!

Table G: Noise Diode Options

	RECEIVER								
Lamp	**327**	**430**	**610**	**LBN**	**LBW**	**SB**	**SBW**	**CB**	**XB**
nocal	X	X	X	X	X	X	X	X	X
lcal		X			X	X	X	X	X
hcal		X			X		X	X	X
lxcal		X			X		X	X	X
hxcal		X			X		X	X	X
l90cal		X			X		X	X	X
h90cal		X			X		X	X	X
lcorcal		X	X	X	X		X	X	X
hcorcal	X	X			X		X	X	X

E.10. Using the AO–Control GUI for Spectral Line Observations

This section describes using the AO-Control GUI – a graphical user interface (GUI) to the Arecibo observing/datataking system – for spectral line observations. If you would like more information on the general properties of the GUI, go to http://www.naic.edu/∼aoui.

E.10.1. A Quick Look

The data-taking computer is located in the control room in Building 1. By the time of your arrival at Arecibo you should have a project directory available to you on this computer. If you do not have a directory, ask your FoT (Friend of the Telescope) to have a project area made for you.

To run the AO–Control GUI (online):

1. Log-in to the data taking computer using the log-in name and password provided by the on-duty Telescope Operator.
2. Ask the Operator if you have control of the telescope
3. Ask the Operator to turn off the TV cameras in the dome (so that it no longer shows the receiver floor) to prevent unnecessary RFI.
4. Type "gui" in the data-taking window

   In the Main GUI Window:
5. Enter your name and proposal i.d. and click "Line"
6. Choose the receiver/IFLO set-up you wish to use
7. Click "Calibrate" to run a calibration scan or two (you probably should do this a few times during the night).
8. Click "Catalog" and choose your source catalog
9. Click "Visible Sources" and choose the source you wish to observe.
   Then click "Yes" to point the telescope

   In the Spectral Line Observer's Widget
10. Choose your set up, either by picking the individual parameters or through loading a file made off line (or go through the set up procedure described above)
11. Review and save your set-up (to be safe)

12. Click "Observe" to observe your source.

    When you're done:

13. Click "Exit VX-Works" to exit AO–Control and move your data

E.10.2. **The Details**

1. Log-in to the data taking computer using the log-in name and password provided by the on-duty telescope Operator.

2. Ask the Operator if you have control of the telescope
You should do this at every telescope...

3. Ask the Operator to turn off the TV monitor cameras (so that it no longer shows the receiver floor). This prevents some potential RFI.

4. **Type "gui" (in the data-taking window)**
This will start up the AO–Control GUI. When you're actually starting observing, this command is traditionally typed in the "data-taking" window at the lower left of the data-taking computer's monitor. You can run the gui on any computer logged into the Arecibo system, but the telescope commands are only implemented when you are logged into the data-taking computer. **NOTE: This means you should not run the gui on the data taking computer unless you are in control of the telescope.** On the other hand, the off-line version of the gui conveniently lets you create your set-up files off line and save them, making your start-up time minimal when you get on the telescope.

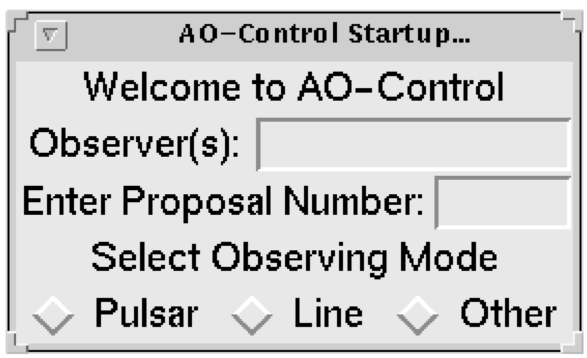

Fig. 3.— *Screen shot of the main AO–Control Startup screen as seen by the observer.*

5. **Enter your name and proposal i.d. Click "Line"**
Figure 3 shows the AO–Control Startup window. **If you do not enter the correct proposal id, your log and data files will be named incorrectly. This is BAD.** If you enter the incorrect proposal id, and/or have a nonstandard file area (this holds mostly for AO staff), you will get a message saying
"! /share/obs4/usr/a9999 does not exist"
At this point (assuming your proposal i.d. is entered correctly and you simply have a nonstandard file area), you simply need to enter the correct path to your file area in the "Default working directory" box that appears.

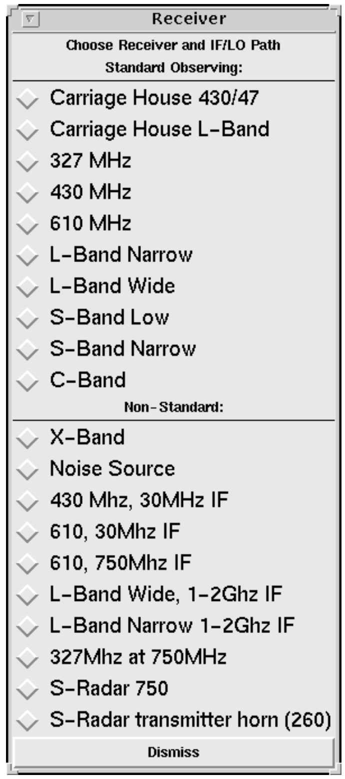

Fig. 4.— *Choosing the receiver and IFLO configuration.*

6. **Choose the receiver/IFLO set-up you wish to use**
   At this point you must choose which receiver and IF set-up you wish to use. Chances are that you will wish to use a Gregorian receiver with a standard IFLO path. That is, you want to choose a receiver from the "Standard Observing" list which is *not* part of the Carriage house (Figure 4).

   The "Non-standard" heading provides a list of both receivers which are still being tested (e.g. receiver has not yet been available long enough for a full pointing model to have been developed) and it lists non-standard configurations for the receivers. As an example. Figure 4 has listed the "L-band Wide, 1-2Ghz IF". Opting for this choice would provide you with the L-band wide receiver, but your signal would get sent through the 1-2GHz down-converter instead of the usual 750MHz down-converter.

   For a list of available receivers, frequencies, and sensitivities, see the above section on Receivers (Section E.2) or go to http://www.naic.edu/techinfo/teltech/upgrade/rec.htm.

7. **Click "Calibrate" to run a calibration scan or two**
   The AO–Control Main Window should now appear (Figure 5) As you are at the beginning of your run, it is a good idea to run a calibration scan or two to check that the telescope is behaving properly. To do this, simply click on the "Calibrate" button in the AO–Control Main Window. A new window will then appear with a list of the calibration sources currently visible to the Arecibo sky (Figure 5). Once you choose a source from this list (by

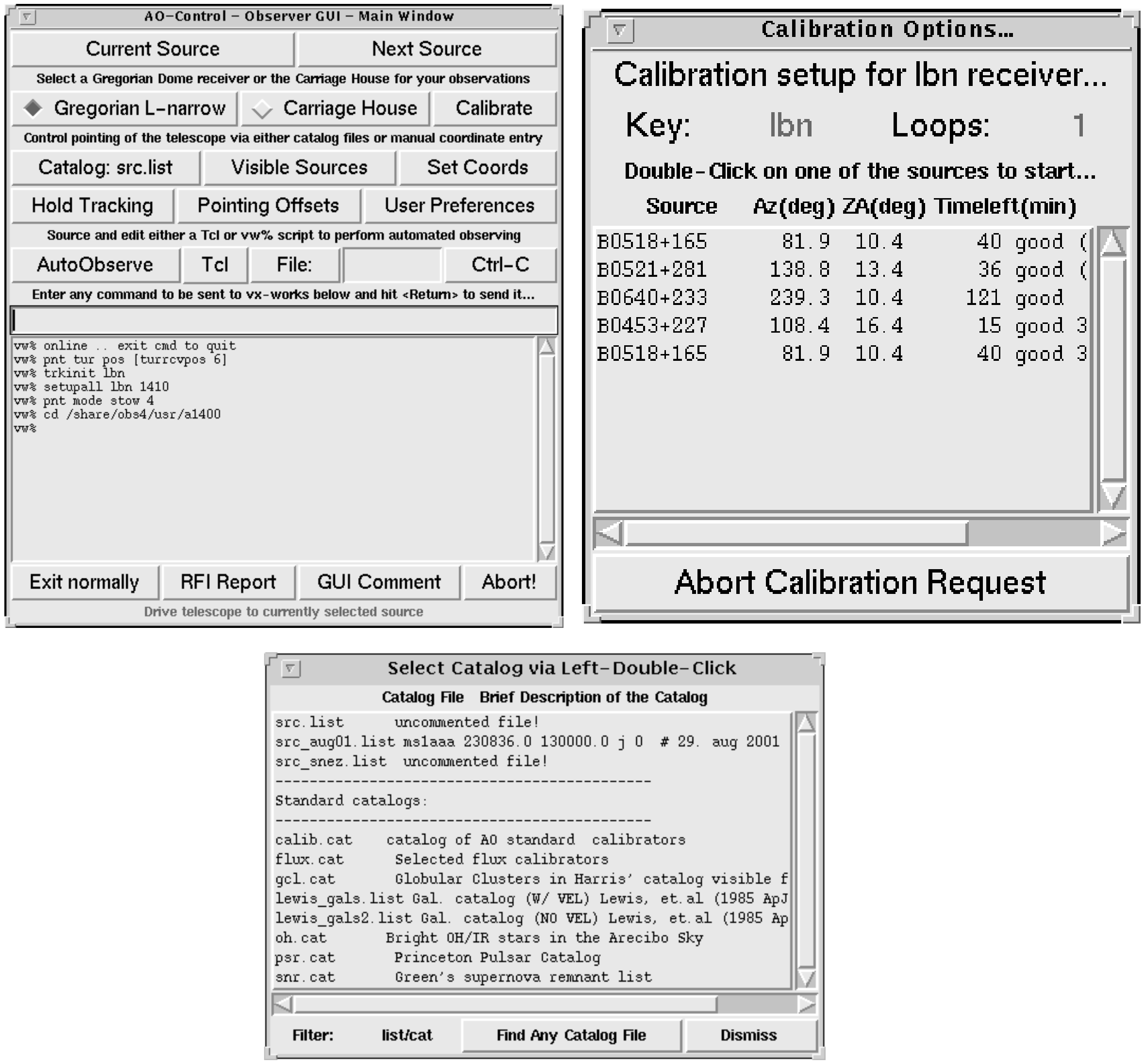

Fig. 5.— *Screen shot of the main AO–Control and the calibration windows seen by the observer.*

double clicking on the source name), the telescope will perform a spider scan on that source, process the data, and give you the results. The source you choose should, ideally, be a point source at your observing frequencies with a well known, non-variable flux density. Sources with "good" in the source list are believed to have well-known, non variable flux densities. Additionally, if no size is listed after the source, it is believed to be $< 15''$ in size.

After the cross scans are complete, a window will appear which shows the results of fitting Carl Heiles' Mueller Matrix routine to the data (Figure 5). With this you can check not only the beam's shape, but also the system temperature, the side-lobe size and pattern, the system gain (in K/Jy), and even the determined source polarization.

Like all telescope calibration, it is a good idea to run this procedure a few times on a few different sources during your run.

8. **Click "Catalog" to choose your source catalog (Main Window)**

To expedite your observing, the next step is to choose the first object in your observing program, and then start the telescope slewing. First, you need to choose your source catalog. If there is a file in your current (working) directory called "src.list," AO–Control will assume this is the source list you wish to use. If it is, life is fine and just go to the next step. If it is not, click on "Catalog" to bring up a window listing all the catalogs available.

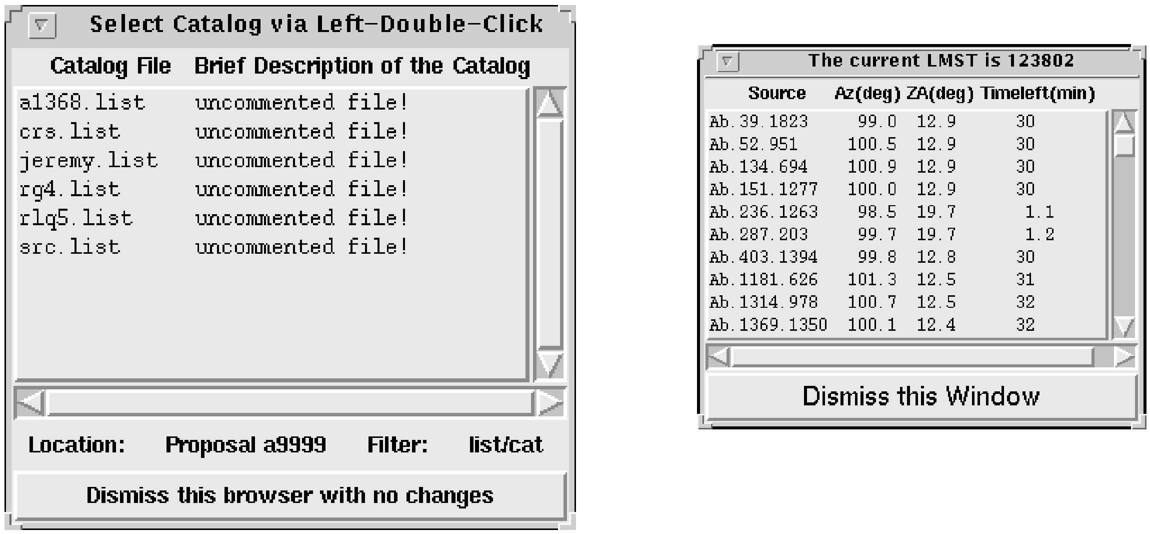

Fig. 6.— *Screen shot of the catalog and visible sources widgets.*

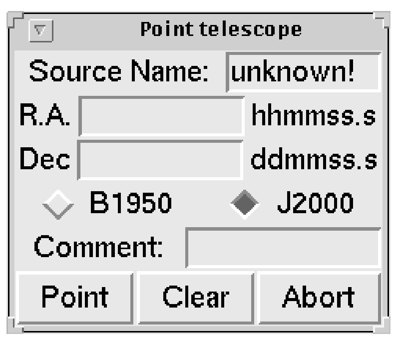

Fig. 7.— *Setting the coordinates for your object.*

If you do not have a working catalog, you can create one by clicking on "Set Coordinates" This will pop up a widget (Figure 7 which asks you for the source name, coordinates, etc. and then (assuming your write permissions are set correctly) enters this information into a file called "src.list" in your working directory. Similarly, if the object you wish to observe is not in a catalog, using the "Set Coordinates" button will append the entered object into your src.list catalog. You can now bypass the next step by simply clicking "point", thereby telling the telescope to slew to your object and begin tracking it. Note that if you wish to enter a velocity for your source in the "Set Coordinates" window, you do so by entering the velocity in the "Comment" section of that window. True comments should be preceded by a "#".

9. **Click "Visible Sources" and choose the source you wish to observe (Main Window)**
   You can now choose your first program source. You should do this as soon as possible to give the telescope time to slew. Choosing a source is done by clicking "Visible Sources" in the Main Window. This causes AO–Control to grab the current catalog file, and determine the current positions of the sources visible at the current local sidereal time.

   After a few seconds, the visible source widget (Fig. 6) will appear. For each source this widget lists the name, approximate Azimuth and Zenith Angles, the remaining time for which you can observe this source today, and any comments you have entered. Sources just about to rise above the telescope zenith angle limit are also displayed. Double clicking on a line containing the source you want to point at will initiate a pointing command. Following a yes/no confirmation that you really want to track this source, (see §E.10.3 if you want to disable this safety feature), AO–Control will point the telescope to your source, and begin tracking it.

10. Choose your observing procedure ("Standard On/Off", "Drift Map", etc.) Once you've selected a receiver, the line observing widget will appear on the screen. Initially, it will look like the widget shown in Fig. 8.

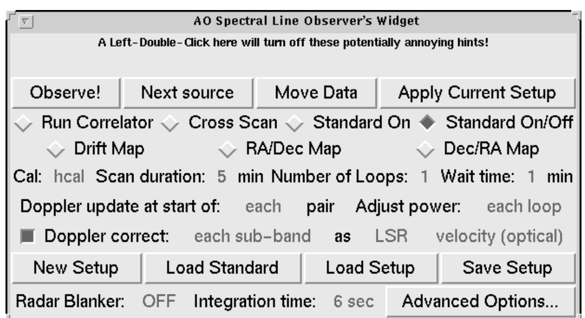

Fig. 8.— *The initial appearance of the spectral line observer's widget*

The first thing you want to do is to choose your observing procedure. (As different procedures have different parameters, you could become frustrated when, after carefully setting your observing parameters, choosing a different observing procedure causes the parameters to be deleted!)

11. **Choose your set-up...**
    You now need to set-up the correlator. The easiest way to do this is to load a pre-existing file. This can either be a file you created off line and then moved into your working directory on the data-taking computer (**being sure to give read/write/execute**

permission to the world so the gui can read and write to it), or it can be one of the "standard" set-up files listed in the Appendices. If you wish to load a standard set-up, click on "Load Standard" and a list of the standard spectral line set-up files will appear. If you wish to choose a file which exists in your working directory, just click on "Load Setup", which will display all spectral line set up files (.sls files) in your working directory. Assuming the set up you want is available, just double click on it and it will automatically be loaded into the Spectral Line Observer's Widget.

If the file you want doesn't already exist, you need to follow the steps below. (Note – you can also use the following steps to modify a currently existing set up, after loading it into the gui – just replace the "New Setup" line below with one of the "Load" steps above.)

- Click "New Setup" to get access to the set up for your first correlator board.
- Enter the center frequency for the 1st board in the box provided This can be the rest frequency or the observed frequency. If you plan on observing one of the standard spectral lines, you can simply click on the "Board 1" button to get a list of commonly observed lines. Double clicking on any of these lines will enter that rest frequency into the frequency box Figure 9.

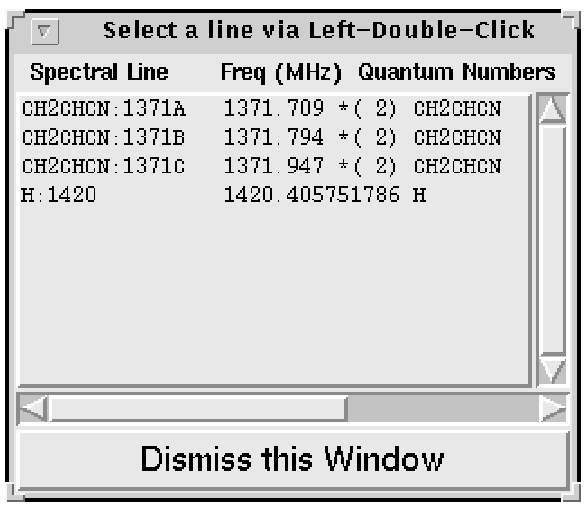

Fig. 9.— *The standard astronomical lines widget*

- Choose the sampling level and polarization(s) for this board from the pull-down menu (Figure 10).
- Choose the bandwidth for this board from the pull-down menu.
- Choose the number of lags/subcorrelator you wish to use from the pull-down menu. **NOTE: The sampling level, bandwidth, and number of lags/subcorrelator are closely interconnected.** As a result, if you wish to have, i.e. 50-MHz bandwidth you cannot have 9-level sampling. So to get the 50-MHz option you must first choose a

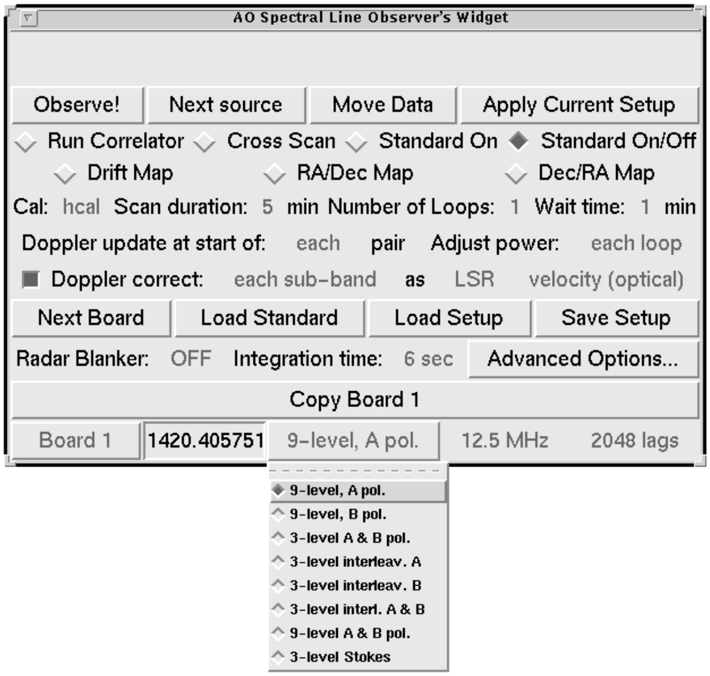

Fig. 10.— *The pull-down menu for setting the sampling levels & board polarization*

3-level sampling option. A table describing all the allowed options is given in the Appendices.

- Assuming you want more than one correlator board (there are four independent boards available for use), you can now either click on "Next Board" or "Copy Board" to enable you to enter the information for the next board. Repeat this process until you've set up all the boards you wish to use.
- You must now decide how long an integration time to use. This is the total integrated time for each data record, and is the indivisible time unit in which your data will be taken. The standard units (1s, 6s, 10s, 30s, & 60s) are given in a pull-down menu. You can obtain a non-standard setting by clicking on the "Advanced Options" button and changing either your dump time and/or your total number of cycles/integration (these multiply together to give you your total integration time).

  The "Advanced Correlator Options" widget also allows you to set when the correlator begins taking data. I.e. if you set this to 10 seconds, the correlator will begin taking data only when the time is at a interval divisible by ten seconds, e.g. 12:01:00, 12:01:10, 12:01:20, whereas if you set this to 1 second the correlator will take data every second. The default value is 1 second.
- If you're using the L-wide receiver (and only if you're using the L-wide receiver), you must now make the following choices:

  - Do you want to use Circular or Linear polarization (the default is circular)
  - Which r.f. filter do you want to use? The ranges available for each filter can be found by clicking on the red numbers after "Filterbank". You can also choose to let AO–Control choose the filter for you. This means you're letting AO–Control decide the optimum filter for your use. Note that if you choose this option, be sure that the frequency at which you observe (the redshifted frequency) falls within the chosen filter.
- At this point you need make choices based on the observing procedure which you chose. These choices are carefully outlined in Section E.3.

12. **At this point it is strongly advised that you save your current set up**

13. **FINALLY – Click "Observe" and start taking data**

14. **When you're done** for the day, be sure to click "Exit VX-Works" to exit AO–Control and move your data.

    Your data will then be moved to "/share/olcor/corfile.<date>.<proj>.#" where <date> is the current date (i.e. 13 March, 2000 is 13mar00); <proj> is your project i.d. (i.e. a9999); # guarantees your data file will have a unique number by incrementing this number every time you invoke the "mvdata" command. So if this is the second time you've moved the data today (12 January, 2000) for your project (a9999), your data will be moved to: /share/olcor/corfile.12jan00.a9999.2.

E.10.3. **Useful Stuff**

- **Stop taking data** If you wish to abort the current procedure, just click "Interrupt" on the Spectral Line Observer's Widget. Note that this option doesn't appear until *after* you have started observing, and the data taking will not stop until after the current integration is complete.

- **Moving Data** You can move the data anytime the correlator is not busy simply by hitting the "Move Data" button in the AO Spectral Line Observer's Widget. You should be aware that you create a new data file every time you move your data. This can be very inconvenient for analyzing data in, e.g. Analyz. Also, until you re-point whichever monitoring program you are using, this will also result in the monitoring program looking at the old file.

- **Configure AO–Control**

  If you have been trying out AO–Control while reading these pages, you will have noticed by now that it likes to ask the user for confirmation before it issues a number of commands to the data-taking program. For example, rotating the turret, pointing the telescope to a source in the catalog all require this by default. While this helps to trap occasional gaffs made by first-time users to the system, more experienced users will find these constant confirmation requests rather irritating since it may result in far too many mouse clicks being required from the user — this is almost as bad as too much typing!

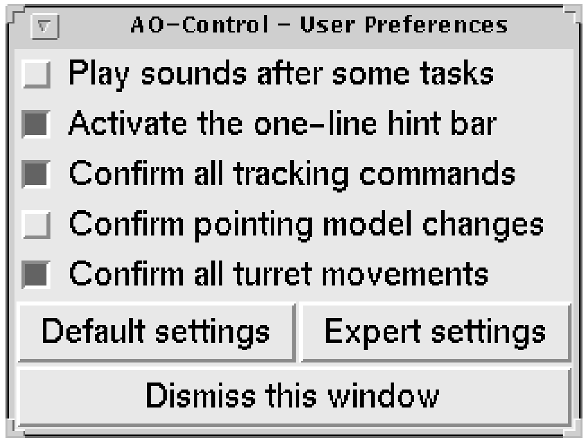

Fig. 11.— *Screen shot showing the user preferences widget, with the "sound" option turned off.*

To minimize the number of confirmation requests, and switch off the little one-line hints at the bottom of the main window, a configuration widget can be invoked by clicking on the "User Preferences" button in the AO-control window. Fig. 11 shows the layout of this widget and its default settings. Expert users can disable all help and confirmation requests by simply hitting "Expert Settings".

You can also turn off the sounds with this gui.

- **Send E–mail**

  The AO–Control main window provides two buttons for sending E-mail at any time during the observing run.

  The "RFI Report" button invokes a mail compose window in which you can type your gripes about radio frequency interference directly to the RFI group at Arecibo. If you are seeing interference, it is **very** important that you report it. **If you do not report the RFI you see, we cannot do anything about it!!** And the better you can characterize the RFI (center frequency, rate of occurrence, polarization, strength, line width, etc) the more readily the folks at Arecibo will be able to track it down.

  Similarly, the "GUI Comment" button allows you to send mail to those people at Arecibo affiliated with the GUI, concerning any aspect of the GUI (bugs, strange features, suggestions, etc). Both these mail options should prove useful, particularly at 3 a.m. when the comments are fresh in your mind.

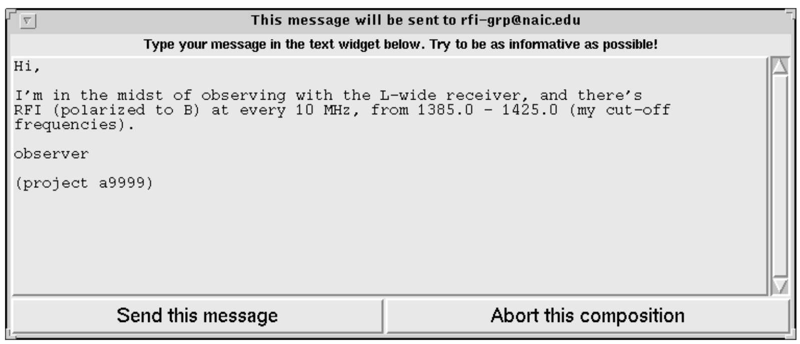

Fig. 12.— *Screen shot showing a sample mail reporting RFI.*

E.11. Online Displays

E.11.1. AO Display Status

You can get the real time status display screen for Arecibo by typing the following (on an Arecibo system):

/home/aoui/display/solaris/aostatus

E.11.2. Real Time Data Display

You can now use IDL to display your data as it comes from the telescope. This is done via the following commands (note that IDL is not case-sensitive):
% gousr
% cd a9999 [or whatever your project number is
% idl
IDL> @corinit
IDL> openr,lun,'/share/olcor/corfile',/get_lun
IDL> cormon,lun
To stop the online display, just hit control-C in the IDL window. If you wish to change the horizontal or vertical axis, just type ver,low,high or hor,low,high . Other Arecibo-relevant IDL commands can be found online at http://www.naic.edu/~phil/cordoc.html.

F. Notes Relevant to Spectral-Line Calibration

Chris Salter

F.1. Relevant Definitions

Antenna Temperature (T_A): Suppose that a telescope is observing a point source of flux density, S. Now suppose that the telescope feed is replaced by a resistor whose temperature, T, is adjusted until the noise power received from the resistor, ($P = k\mathrm{T}\Delta\nu$, where k is Boltzmann's constant $= 1.38 \times 10^{-23}$ Joule K^{-1}, and $\Delta\nu$ is the receiver bandwidth), equals that previously received from the point source. If the temperature of the resistor is then T_A, this is known as the antenna temperature due to the source.

System Temperature (T_{sys}) is the total system noise expressed as an Antenna Temperature. At Arecibo, T_{sys} is essentially a monotonic function of zenith angle, za. To first order, T_{sys} is;

$$\mathrm{T}_{sys}(za) = \mathrm{T}_{rx} + \mathrm{T}_{gr}(za) + \mathrm{T}_{atm}(za) + \mathrm{T}_{cel}(\alpha, \delta, za) \qquad (1)$$

Where, a) T_{rx} is the receiver temperature; b) T_{gr} is the contribution from the ground due to spillover, vignetting, etc. This is likely to also be a weak function of azimuth; c) T_{atm} is the contribution from the atmosphere which will generally increase as frequency increases. At wavelengths shorter than about λ11 cm, especially in adverse weather conditions, T_{atm} can vary significantly on the time scale of a few tenths of a second; d) T_{cel} is the celestial contribution, which can be roughly expressed as;

$$\mathrm{T}_{cel} = \mathrm{T}_{CMB} + \mathrm{T}_{BG}(\alpha, \delta) + \mathrm{T}_{source}(za) \qquad (2)$$

Where T_{CMB} is the contribution from the Cosmic Microwave Background (~ 2.7 K), T_{BG} is the contribution from the celestial "background" radiation such as the galactic "background" emission and individual confusing sources, and T_{source} is the contribution of the source itself which will be a function of zenith angle.

Telescope Gain (G) is the telescope response to a point source. At Arecibo, this is usually expressed as the antenna temperature, T_A, due to a point source of flux density 1 Jy lying at the peak of the telescope beam, and has units of K/Jy. G has a marked, monotonic variation with zenith angle at Arecibo, i.e. $\mathrm{G} = \mathrm{G}(za)$. At present it also has an azimuth dependence which becomes more marked as frequency is increased. At least part of this azimuth dependency is thought to be due to imperfections in the figure of the primary reflector that vary around the surface. These surface imperfections are expected to be rectified in the coming months.

[**N.B.** It should be noted that the above definition of gain is intimately connected with the Directivity of the telescope, D, the ratio of the radiated intensity at the beam center to the average radiated power (with the telescope transmitting.) D is related to the effective telescope area, A_{eff}, by $D = 4\pi A_{eff}/\lambda^2$. In equation (5) below it is shown that $A_{eff} = 2k$G, so $D = 8\pi k G/\lambda^2$, and thus $D \propto G$.]

System Equivalent Flux Density (SEFD) is the system temperature expressed as an equivalent point-source flux density. It has the units of Jy. It is not an independent quantity, but depends on the system temperature and telescope gain via;

$$\mathrm{SEFD}(za) = T_{sys}(za) \ / \ G(za) \qquad (3)$$

It is to be noted that SEFD can be estimated rather accurately by measurements of a point source of known flux density without recourse to secondary standards such as noise-diode calibrations. The major source of error in the measured SEFD will usually be the uncertainty of the flux density of the point source.

To illustrate the above, if a point source of known flux density, $S(\nu)$, is measured using ON/OFFs, cross-scans, or turret-scans, then if ON is the total signal when pointing directly at the source, and OFF is the signal at an adjacent off-source position (assumed to be "blank sky"), then;

$$\mathrm{SEFD}(za) = S(\nu) * \mathrm{OFF} \ / \ [\mathrm{ON} - \mathrm{OFF}] \qquad (3a)$$

Note that to obtain the total signals, ON and OFF, the "true zero" of the total-power signal needs to be known (e.g. via the correlator or appropriate setting of the continuum system).

Note too that no noise-diode measurement needs be taken, though its presence makes simultaneous computation of T_{sys} and G possible. If indeed no noise-diode measures are made, T_{sys} values relative to that at some preferred zenith angle za_0 can still be calculated by $T_{sys}(za)/T_{sys}(za_0) = \mathrm{OFF}(za)/\mathrm{OFF}(za_0)$. Then, once the SEFD has also been computed, the normalized telescope gain, $G(za)/T_{sys}(za_0)$, can be calculated from,

$$\frac{G(za)}{T_{sys}(za_0)} = \frac{T_{sys}(za)/T_{sys}(za_0)}{\mathrm{SEFD}(za)} \qquad (4)$$

If $T_{sys}(za_0)$ is known, then $T_{sys}(za)$ and $G(za)$ can be expressed in units of K and K/Jy respectively.

As there may be azimuth dependencies to both T_{sys} and G at present, there also also be an azimuth dependency to SEFD.

Effective Area (A_{eff}) is the equivalent area over which radiation would have to be collected with perfect efficiency to give the same telescope gain as the actual telescope. For radiation from a point source of flux density, S, producing an antenna temperature, T_A;

$$\frac{1}{2}\mathrm{S}A_{eff} = kT_A$$

So, $$A_{eff} = 2k\ G \quad (5)$$

Where, $$G = T_A/S$$

As an example, G = 8 K/Jy would result from an effective area of 22,080 m^2, which would be a circular aperture of diameter 168 m. Note that A_{eff} is also a function of zenith angle (and increasingly azimuth at higher frequencies) at Arecibo.

F.2. Possible Calibration Approaches

Using a Standard SEFD Curve: If an ON/OFF measurement has been made, then;

$$\mathrm{Signal(Jy/beam)} = \mathrm{SEFD}(za) * \frac{[\mathrm{ON-OFF}]}{\mathrm{OFF}} \quad (6)$$

SEFD(za) could be taken from a standard curve, or be measured especially for the individual measurement using a continuum source of known flux density and applying equation(3a). In the above, we assume that T_{sys}/G is independent of frequency across the band, which is probably not true due to the presence of standing waves, etc.

N.B. T_{sys} in the OFF position at a given zenith angle may not be the same as when the standard curve was measured due to a) the presence of a confusing source "in the OFF", b) the increasingly large continuum "background" contribution at lower galactic latitudes and frequencies, and/or c) secular changes in T_{sys} since the SEFD curve was last measured. However, these effects can often be corrected for by estimating the increment to the SEFD from $\Delta\mathrm{SEFD} = \Delta T_{sys}/G(za)$.

Using the Noise Diode Calibration and a Standard Gain Curve: Suppose CAL_{ON} and CAL_{OFF} measurements are made along with an ON/OFF source measurement. Also suppose that the antenna temperature of the noise diode signal (i.e. CAL_{ON} – CAL_{OFF}) is T_{cal}, a value which is the same at all zenith angles. Then, the system temperature is given by;

$$\mathrm{T}_{sys}(\mathrm{K}) = \mathrm{T}_{cal} * \frac{\mathrm{CAL}_{OFF}}{[\mathrm{CAL}_{ON} - \mathrm{CAL}_{OFF}]}$$

and the antenna temperature of the source is;

$$\mathrm{T}_{source}(\mathrm{K}) = \mathrm{T}_{cal} * \frac{\mathrm{CAL}_{OFF}}{[\mathrm{CAL}_{ON} - \mathrm{CAL}_{OFF}]} * \frac{[\mathrm{ON} - \mathrm{OFF}]}{\mathrm{OFF}}$$

(where CAL_{OFF} can be taken to be essentially equal to OFF.)

Thus;

$$\mathrm{Signal(Jy/beam)} = \frac{\mathrm{T}_{cal}}{\mathrm{G}(za)} * \frac{\mathrm{CAL}_{OFF}}{[\mathrm{CAL}_{ON} - \mathrm{CAL}_{OFF}]} * \frac{[\mathrm{ON} - \mathrm{OFF}]}{\mathrm{OFF}} \qquad (7)$$

So if G(za) and T_{cal} are known, the observation can be simply converted into Jy/beam using equation (7).

[**N.B.** It should be noted that;

$$\mathrm{SEFD}(za) = \frac{\mathrm{T}_{cal}}{\mathrm{G}(za)} * \frac{\mathrm{CAL}_{OFF}}{[\mathrm{CAL}_{ON} - \mathrm{CAL}_{OFF}]}$$

Therefore, equation (7) reduces to;

$$\mathrm{Signal(Jy/beam)} = \mathrm{SEFD}(za) * \frac{[\mathrm{ON} - \mathrm{OFF}]}{\mathrm{OFF}}$$

This is identical to equation (6). Thus, this method is not in any way in conflict with that using a standard SEFD curve, and the user can select whichever of the two they feel represent the present status of the system best. This second method does not assume that the T_{sys} is the same as when a standard SEFD curve was measured. Nevertheless, it does assume that $\mathrm{G}(za)$ has remained unchanged since the gain curve used was last measured, and that T_{cal} does not vary with time.]

Using a Continuum Calibrator of Known Flux Density: When applied to spectral-line calibration, both of the above approaches ignore likely changes across the passband, i.e. the same functions for SEFD(za) and G(za), plus the value for T_{cal}, are assumed to apply across the whole passband. In practice this is not the case. For example, if the line emitter has significant continuum emission associated with it, or a significant continuum source is present in either the ON or OFF beam, or the line is wide, then standing waves modulating the effective passband response may result in poor baselines. This can be largely overcome, (though at a theoretical cost in sensitivity/observing time – see below), by interspersing identical ON/OFF measurements of a continuum "calibrator" source, covering as near as possible the same tracks across the primary reflector (i.e. the same azimuth-zenith angle tracks). The calibrator source would ideally have a well-established flux density (i.e. not be significantly variable), and preferably be of similar flux density to that of the target field. The tolerance to this latter point presently needs evaluation.

For identical ON/OFF pairs on a target and a calibrator source observed quasi-simultaneously over the same range of azimuth and zenith angle,

$$\text{Signal(Jy/beam)} = \text{S}_{c\_cal} * \frac{\text{OFF}_{c\_cal}}{[\text{ON}_{c\_cal} - \text{OFF}_{c\_cal}]} * \frac{[\text{ON}-\text{OFF}]}{\text{OFF}} \qquad (8)$$

Where S_{c_cal} is the flux density of the continuum calibrator source in Jy at the observing frequency.

The cost paid is best illustrated by considering the rms, $\sigma_{\text{T}}(\text{K})$, for observations with a receiver of system temperature, T_{sys}, bandwidth, β, and total integration time per observing cycle, τ. For the following specified cases, the theoretical sensitivities are;

- **Total-Power Observations:** Here all the observing time is spent looking at the target. This gives, $\sigma_{\text{T}} = \text{T}_{sys}/\sqrt{(\beta\tau)}$.
- **"In-Band" Frequency switching:** Here the line is always in the observing band, but at each of the two frequency positions where it falls, only one half of the time is spent looking at the line. This gives, $\sigma_{\text{T}} = \sqrt{2}\text{T}_{sys}/\sqrt{\beta\tau}$.
- **Position Switching or "Out of Band" Frequency Switching:** Here the line is only observed for one half of the time, with noise observed all of the time. This gives, $\sigma_{\text{T}} = 2\text{T}_{sys}/\sqrt{\beta\tau}$.
- **Position Switching on a Target Source, and a Band-Pass Continuum Calibrator:** Here the line is observed for one quarter of the time, but noise is observed all the time. This gives, $\sigma_{\text{T}} = 4\text{T}_{sys}/\sqrt{\beta\tau}$. Note that T here is not just the "blank-sky" system temperature, but should include the contribution due to the continuum emission of the target and calibrator, i.e. if both the sources have a flux density, S Jy, then T_{sys} should be increased by $\Delta\text{T}_{sys}(K) = S * \text{G}(za)$.

F.3. Radial Velocities

Optical Velocities: Optical astronomers traditionally use wavelengths to define redshifts and radial velocities. **It is important to note that these days almost all radio astronomers do the same!** If z_{opt} is the the optically defined redshift, and v_{opt} the optically defined (non-relativistic) radial velocity for a line emitted at wavelength, λ_0, and observed at a wavelength, λ, then;

$$z_{opt} = \frac{(\lambda - \lambda_0)}{\lambda_0} = v_{opt}/c \qquad (9)$$

N.B. v_{opt} only represents a true velocity if $v \ll c$). However, it is usual to present radial velocities as $v = cz$, meaning that this "velocity" is really a "scaled redshift".

Radio Velocities: In the early days of radio astronomy, its practitioners used frequencies to define redshifts and radial velocities. If z_{rad} is the the radio defined redshift, and v_{rad} the radio defined (non-relativistic) radial velocity for a line emitted at frequency, ν_0, and observed at a frequency, ν, then;

$$z_{rad} = \frac{(\nu_0 - \nu)}{\nu_0} = v_{rad}/c \tag{10}$$

¿From equations (10) and (11), it follows that for a given target, $(z_{opt}/z_{rad}) = \lambda/\lambda_0$.

F.4. Relating $\mathbf{T}_A$ to $\mathbf{T}_b$

In discussing this issue, the formalism of Seeger et al. (B.A.I.N., 1965, **18**, 11) is followed.

Yet More Definitions: The antenna power pattern, $f(\theta, \phi)$ is the power response to an unpolarized wave arriving from the direction (θ, ϕ), where the maximum response is normalized to be, $f(0, 0) = 1$.

The antenna solid angle is the integral of $f(\theta, \phi)$ over the whole sphere, $\Omega = \int\int_{4\pi} f(\theta, \phi) d\Omega$. Note that $\Omega = 4\pi/\mathrm{D} = \lambda^2/\mathrm{A}_{eff} = \lambda^2/2k\mathrm{G}$, where G is as defined in Section 1.

The "full beam" is defined to be that part of the antenna beam which which one is interested for a particular observation, giving a full-beam solid angle of $\Omega_{\mathrm{fb}} = \int\int_{\mathrm{fb}} f(\theta, \phi) d\Omega$. (Note that if the full beam were to be Gaussian down to zero, then $\Omega_{\mathrm{fb}} = 1.133\theta_V \theta_H$, where θ_V and θ_H are the orthogonal half-power widths.) Now the full-beam efficiency is defined as,

$$\eta_B = \Omega_{\mathrm{fb}}/\Omega \quad < 1 \tag{11}$$

The brightness temperature of the sky, T_b in a given direction is the temperature of a black body situated in that direction for which the brightness of the thermal radiation would equal the brightness of the sky, B. For the Rayleigh-Jeans approximation, $\mathrm{T}_b = \lambda^2 \mathrm{B}/2k$.

We can define a full-beam brightness temperature, T_{fb}, to be the weighted mean of the brightness temperature over the full beam, i.e.,

$$\mathrm{T}_{\mathrm{fb}} = \frac{1}{\Omega_{\mathrm{fb}}} \int\int_{\mathrm{fb}} f(\theta, \phi) \mathrm{T}_b(\theta, \phi) d\Omega \tag{12}$$

Now the observed Antenna Temperature due to the whole sky, T_A, is,

$$T_A = \frac{1}{\Omega} \int\int_{4\pi} f(\theta,\phi) T_b(\theta,\phi) d\Omega \qquad (13)$$

So,

$$T_A = \frac{\eta_B}{\Omega_{\rm fb}} [\int\int_{fb} f(\theta,\phi) T_b(\theta,\phi) d\Omega + \int\int_{4\pi - fb} f(\theta,\phi) T_b(\theta,\phi) d\Omega]$$

If the full beam is a very small fraction of 4π steradians, we can take the second term as being constant over a measurement. This then gives,

$$T_A = \eta_B T_{\rm fb} + \text{ constant} \qquad (14)$$

Thus the constant of proportionality between the antenna and full-beam temperatures is η_B. As $\Omega = \lambda^2/2k$G, and $\Omega_{\rm beam}$ can be obtained from integrating a "beam map" made over the area of the adopted full beam, η_B can be derived via equation (11), and hence measured antenna temperatures turned into full-beam brightness temperatures.

N.B.: As G = G(za), and $\Omega_{\rm fb} = \Omega_{\rm fb}(za)$, η_B will also be a function of zenith angle unless $\Omega_{\rm fb}(za) \propto 1/G(za)$.

One "full beam" whose solid angle is well defined is the "Moon beam", which is that area of the beam lying within a circle of the same radius as the Moon. If the true brightness temperature of the Moon at the observing frequency (a well tabulated function) is T_b(Moon), and an antenna temperature of T_A(Moon) is measured for the Moon, then η(Moon) = T_A(Moon)/T_b(Moon). In addition, now that Ω and $\eta_{\rm Moon}$ are known, $\Omega_{\rm Moon}$ can be derived from equation (11).

G. Revised Morphological Types

This description is an excerpt from the Documentation for the Computer-Readable Version of the Second Reference Catalogue of Bright Galaxies (RC2)*, catalogue numbered* **VII/122***, prepared by Theresa A. Nagy and Robert S. Hill (April 1981), revised by Suzan E. Gessner and Lee E. Brotzman (December 1990) for NASA Goddard Space Flight Center, Greenbelt, MD 20771*

G.1. Coding of revised morphological types

Classes	Families	Varieties	Stages	T	Type	Code
Ellipticals		Compact		−6	cE	cE...
			Ellipt. (0–6)	−5	E0	.E.0.
			Intermediate	−5	E0–1	.E.0+
		"cD"		−4	E+	.E$^+$..
Lenticulars					S0	.L
	Non-barred				SA0	.LA
	Barred				SB0	.LB
	Mixed				SAB0	.LX
		Inner ring			S(r)0	.L.R
		S-shaped			S(s)0	.L.S
		Mixed			S(rs)0	.L.T
			Early	−3	S0$^-$	.L..−
			Intermediate	−2	S0°	.L..0
			Late	−1	S0$^+$	.L..+
Spirals	Non-barred				SA	.SA
	Barred				SB	.SB
	Mixed				SAB	.SX
		Inner ring			S(r)	.S.R
		S-shaped			S(s)	.S.S
		Mixed			S(rs)	.S.T
			0/a	0	S0/a	.S..0
			a	1	Sa	.S..1
			ab	2	Sab	.S..2
			b	3	Sb	.S..3
			bc	4	Sbc	.S..4
			c	5	Sc	.S..5
			cd	6	Scd	.S..6
			d	7	Sd	.S..7
			dm	8	Sdm	.S..8
			m	9	Sm	.S..9
Irregulars	Non-barred				IA	.IA
	Barred				IB	.IB
	Mixed				IAB	.IX
		S-shaped			I(s)	.I.S
			Non-Magellanic	90	I0	.I.0
			Magellanic	10	Im	.I..9
		Compact		11	cI	cI
Peculiars				99	Pec	.P
Peculiarities			Peculiarity		pec	.....P
(All types)			Uncertain		:	....*
			Doubtful		?	....?
			Spindle		sp	...../
			Outer ring		(R)	R......
			Pseudo-outer R		(R′)	P......

G.2. Conversion of Hubble Types to Revised System

Hubble	Revised	T
E	E	-5
E-S0	L-:	-3:
S0	L	-2
IrrII	I0	0:
S0/a	S0/a	0
Sa	Sa	1
Sa-b	Sab	2
Sb	Sb	3
Sb-c	Sbc	4
Sc	Scd:	6:
Sc-Irr	Sdm:	8:
IrrI	Im	10
S...	S.	3?
S"early"	S.(Sa?)	1?
S"late"	S.Sc?	5?

G.3. Codes for telescope sources of revised types

Observatory	Tel. Ap. (in.)	Code	Observatory	Tel. Ap. (in.)	Code
Palomar	200	P200.	Mt. Wilson	60	W060.
Lick	120	L120.	Tautenburg	52	T052.
Mt. Wilson	100	W100.	Palomar (prints)	48	P048.
McDonald	82	M082.	Palomar (glass)	48	PG48.
Radcliffe	74	R074.	ESO	40	E040.
Mt. Stromlo	74	S074.	Siding Spring	40	S040.
USNO (Flagstaff)	61	N061.	Lick	36	L036.
Boyden	60	B060.	Mt. Stromlo	30	S030.
Cordoba	60	C060.			

G.4. Codes for author sources of revised types

Code	Reference
....B	Buta, R., Publ. Warner and Swasey Obs., II, in press, 1976
....C	Corwin, H. G., Publ. Dept. Astr. U. Texas, II, 2, No. 12, 1968; II, 3, No. 5, 1970; PASP, 83, 320, 1971; unpublished 1971-1975.
....F	Fisher, J. R., and Tully, R. B., A&A, 44, 151, 1975
....H	Holmberg, E., et al., A&AS, 18, 463 and 491, 1974
....N	Nilson, P., UGC, 1973; Uppsala Obs. Rep. No. 5, 1974
....R	Rood, H. J., and Baum, W. A., AJ, 72, 398, 1967
....V	de Vaucouleurs, G., ApJS, No. 74, 1963; RC1, 1964; unpublished 1964-1975.

G.5. Codes for Yerkes (Morgan) types

Classes	Type	Code	Classes	Type	Code
Elliptical	E(0-7)	E0	Irregular	I	I
	E-D	ED		S-I	SI
	D-E	DE		I-S	IS
	S-E	SE		I-B	IB
Dusty		D		B-I	BI
	D-S	DS	Peculiarities	L(1)	..L
	S-D	SD		P	..P
Spiral	S	S		?,:	*
				Color Classes	Code
Barred	B	B		a	A
	(B)	SX		af	AF
	B-S	BS		f	F
	S-B	SB		fg	FG
				g	G
				gk	GK
				k	K
				:	*

(1) Low surface brightness

G.6. Coding of DDO (van den Bergh) Types

Classes	Families	Stages	Type	Coding	Notes
Elliptical		Ellipcicity (0-9)	E0	E 0	(1)
Sprial	Ordinary		S	S	
	Barred		SB	S B	
	Intermediate		S (B)	S X	
		a	Sa	S 0	
		b-	Sb-	S 2	
		b	Sb	S 3	
		b+	Sb+	S 4	
		c	Sc	S 5	
		-	S-	S 6	
		+	S+	S 7	
Irregular			Ir	I	
			Ir+	I 9	
Peculiar			P	P	
Peculiarities		Bright nucleus	N	N	
		Nebulous arms, mild case	(n)	N-	(2)
		Nebulous arms, normal	n	N	
		Nebulous arms, extreme	nn	N+	
		Patchy arms, mild case	(*)	K-	
		Patchy arms, normal	*	K	
		Patchy arms, extreme	**	K+	
		Distorted arms,mild case	(t)	T-	
		Distorted arms, normal	t	T	
		Distorted arms, extreme	tt	T+	
		Peculiarity	p	P	
		Uncertain ?,:,()		* * *	(3)
Luminosity Classes	Code	Luminosity Classes	Code		
I	1	III-IV	6		
I-II	2	IV	7		
II	3	IV-V	8		
II-III	4	V	9		
III	5				

(1) Includes lenticulars, especially in ES, E9

(2) Combined cases are coded NK, NT, etc

(3) Applies to symbol or group of symbols immediately preceding it

H. Optical-to-HI Ratios versus Morphological Types