Radio Astronomy for Chemists

I. Introduction:

The activities at the telescope for this school consist of two sections. Part I will involve observations of several different molecules (HCN, CH_3CN, HC_3N, SiO, and CO) in a sample of representative sources. These measurements are designed to illustrate some basic principles of molecular-line radio astronomy. This section will be conducted during the first 8 hour observing period. The second section (next 8 hour slot) will be a CCU group project, conducting the initial measurements of a spectral-line survey using the new ALMA Band 3 (3 mm) receiver of three carbon-rich circumstellar shells: IRC+40540, CIT-6 and CRL-2688. This project can be continued using remote observing for those interested in more observations and improving their skills.

Part I will consist of the following measurements:

1) **HCN**: The hyperfine structure in the $J = 1 \rightarrow 0$ transition will be used to evaluate the opacity in this line. Opacity is an important concept in molecular line radiative transfer.

2) **CH_3CN**: The $J = 8 \rightarrow 7$ transition of this symmetric top consists of K-ladder structure, which can be used to estimate the gas kinetic temperature of the object observed.

3) **HC_3N**: Here a series of transitions will be observed to extract a column density and a rotational temperature, using the simplistic “rotational diagram” method.

4) **SiO**: Transitions will be observed here to illustrate the non-thermal nature of many circumstellar and interstellar molecular sources.

5) **CO**: The $J = 1 \rightarrow 0$ transition will be observed in a variety of sources, including an external galaxy, to demonstrate the varied dynamical information contained in molecular line profiles. A small map will be conducted towards a dense cloud to illustrate the extended nature of molecular emission.

In Part II, two to three frequencies of a future broadband spectral-line survey will be measured with high sensitivity. Spectral features will be identified. These data are potentially publishable.

II. Observations:

Part I: Individual Exercises:

HCN: Here the $J = 1 \rightarrow 0$ transition near 88 GHz will be observed in a cold, dark cloud: **L134N**, **L673**, or **TMC-1**. These sources have very low kinetic temperatures ($T \sim 10$ K), and thus have resolvable hyperfine splittings, arising from the N nucleus. Three hyperfine components should be present in the spectrum. The ratio of these lines will be used to examine the optical depth in these clouds.

CH_3CN: In this case, the J = 8 → 7 transition will be observed near 147 GHz towards a hot core source either **W51M**, **G34.3**, or **Orion-KL**. CH_3CN is a symmetric top, and hence has two different moments of inertia, requiring the energy level pattern to be characterized by two quantum numbers, J and K. As a result, the J = 8 → 7 transition actually consists of a pattern of lines, labeled by quantum number K, so-called "K-ladder" structure. You will measure the relative intensities of these K-ladders to estimate the kinetic temperature of the gas containing this molecule.

HC_3N: Here multiple rotational transitions will be observed at 3 mm and 2 mm towards **W51M**, **G34.3**, or **Orion-KL**. The observations will be used to construct a "rotational diagram" from which a molecular "column density" can be extracted, as well as the rotational temperature of the gas-phase HC_3N. You will have to switch receivers for these measurements.

SiO: Here the v = 0, J = 2 → 1 and v = 1, J= 2 → 1 transitions near 86 GHz will be observed towards the circumstellar gas surrounding the stars **Chi Cyg**, **R Leo**, or **R Cas**. The latter transition is from the first excited vibrational state, which lies ~1800 K above the ground state. Note the difference in line shapes between v = 0 and v = 1. Also check if there are differences in line intensity between the two polarizations. Which lines are non-thermal ?

CO: The J = 1 → 0 transition of CO near 115 GHz will be observed towards 1) **L134N**, **L673**, or **TMC-1**; 2) **W51M**, **Orion-KL**, or **G34.3**; 3) **Chi Cyg**, **R Leo**, or **R Cas**, and 4) the external galaxy **M51**. The galaxy is 23 million light years away. In addition, the J = 1 → 0 transition of ^{13}CO near 110 GHz will be studied towards Chi Cyg, R Leo, or R Cas. These observations will allow for kinematic information to be obtained for the four types of sources. The $^{12}C/^{13}C$ ratio will also be obtained for Chi Cyg, R Leo, or R Cas.

The J = 1 → 0 transition at 115 GHz will also be mapped towards the hot cores **W51M**, **G34.3**, or **Orion-KL**. The emission from this molecule is widespread across these regions. Here a 3x3 map will be performed with a grid spacing of 60″ (arcseconds).

Part II: Group Project:

Here you will start a 3 mm spectral survey of the envelopes around the stars **IRC+40540**, **CIT6**, and **CRL2688** using the new ALMA Band 3 receiver. Using the filter banks with 2 MHz resolution, 500 MHz of bandwidth will simultaneously be observed per frequency setting for a period of time sufficient to achieve a low noise level (~ a few hours) After this level is achieved, the next (higher or lower) frequency will be observed 0.5 GHz away, and so forth. A local oscillator (LO) shift should be done halfway through the measurements at each frequency. Which way do the spectral lines move with the LO shift ? Why is this done ?

Observing Procedure

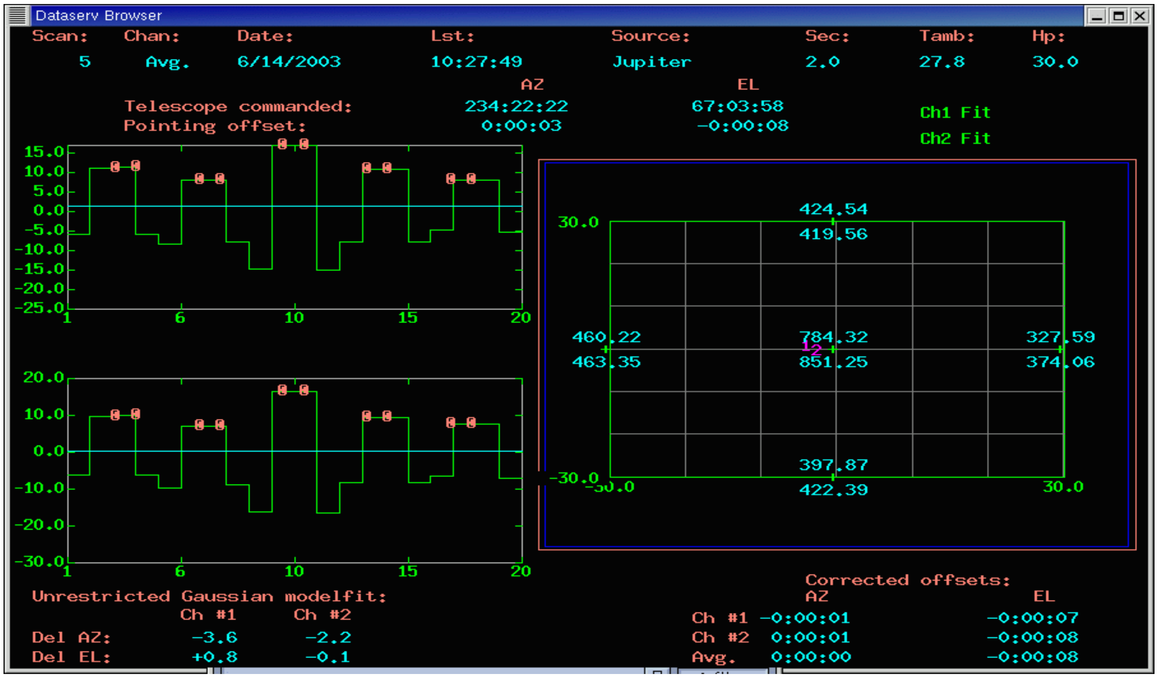
You will begin your observing session by logging into the telescope's observing computer. This procedure will be demonstrated at the telescope. Your user initials will be "CCU".

HCN Observations

The session will begin with observations of HCN. Ask the telescope operator to tune to the HCN: J = 1 → 0 frequency at 88.6318 GHz in the lower sideband (LSB). The operator will tune the local oscillator and radio receiver to this frequency. The operator will ask what source you are observing. You will need to pick a cold cloud that is currently above the horizon (more than 20 degrees in elevation) using Catalog Tool. All sources can be found in the CCU.CAT catalog at the telescope, which contain the their celestial coordinates (in Right Ascension and Declination, α and δ) and V_{LSR}. The V_{LSR} is the Doppler correction for this source relative to the Local Standard of Rest. The telescope control system also corrects the observing frequency for the Earth's rotation and revolution about the Sun, relative to the Local Standard of Rest. All sources have such a Doppler correction.

Once the receiver is tuned, you will have to get to a planet or continuum source to point and focus. First, a pointing "five-point" needs to be done. The operator will move the telescope and measure five positions across the source: approximately half-a-beam width north, south, east and west of the source, plus center position. One of the computers will fit these data points, all which appear on the "Dataserve" terminal. The intensity of the source, in Jy, will appear at the five positions measured as well as pointing corrections in azimuth and elevation, see Figure 1. These are the corrections you will need to "fine tune" the position of the telescope on the sky. A few such pointing scans may have to be done to achieve a consistent set of pointing corrections. The operator will put the new corrections into the telescope drive computer.

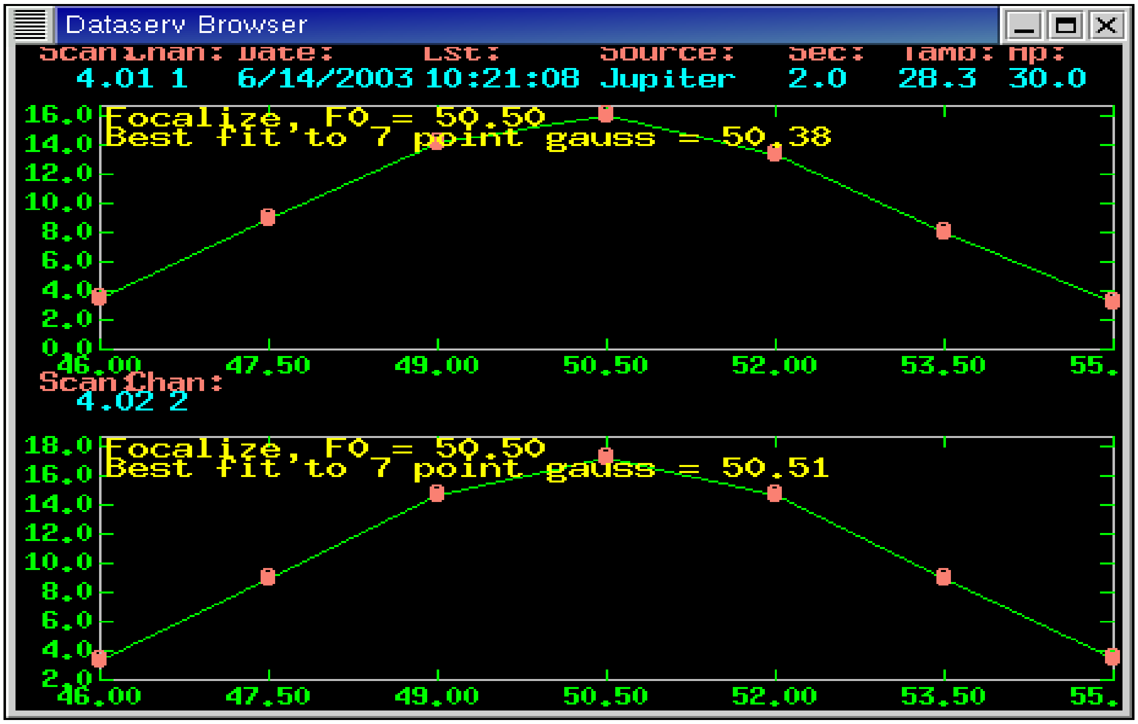
The next task is to focus the telescope. The operator will move the subreflector to a series of different positions and measure the temperature of the source at each position. The



```
Scan:   Chan:     Date:          Lst:          Source:       Sec:     Tamb:    Hp:
   5     Avg.     6/14/2003      10:27:49      Jupiter       2.0      27.8     30.0
                                       AZ                EL
        Telescope commanded:      234:22:22         67:03:58        Ch1 Fit
        Pointing offset:            0:00:03         -0:00:08
                                                                    Ch2 Fit

                                                          Corrected offsets:
Unrestricted Gaussian modelfit:                           AZ                    EL
                  Ch #1        Ch #2               Ch #1 -0:00:01          -0:00:07
Del AZ:            -3.6         -2.2               Ch #2  0:00:01          -0:00:08
Del EL:            +0.8         -0.1               Avg.   0:00:00          -0:00:08
```

Figure 1: A pointing "5-point" scan displayed in "Dataserve."



```
Scan Chan: Date:      LST:     Source:  Sec: Tamb: Hp:
  4.01 1   6/14/2003 10:21:08 Jupiter  2.0  28.3  30.0
Focalize, FO = 50.50
Best fit to 7 point gauss = 50.38
Scan Chan:
  4.02 2
Focalize, FO = 50.50
Best fit to 7 point gauss = 50.51
```

Figure 2: A “focus” scan which shows planet intensity as a function of focus positions.

computer will take the data and produce a plot of focus versus intensity. The curve will increase to a maximum and decrease, see Figure 2. The peak of this curve is the optimal focus position. The computer will also do a fit and print out the optimal focus position. You may have to iterate a few times with the focus.

Next are the spectral line measurements. Give the operator your source name and position from the catalog and he will put in the Doppler correction and steer the telescope to the source.

You will have to tell the operator:

1) Observing procedure: Position-switching, off position: 30 arcminutes west in azimuth
2) Scan time: 6 minutes
3) Spectrometer Backend Set-up: Use filter banks: 100/250 parallel/parallel; MAC: 150_8k_2

The telescope will take data “on” and “off” source to eliminate much of the background noise, with the off-position set in azimuth. The spectrometer set-up places the two receiver polarizations into a 100 kHz and 250 kHz filter banks simultaneously, splitting each bank in half (i.e “parallel mode”: 2 x 128 channels each). The Millimeter Auto Correlator (MAC) is also split into halves for each polarization, using certain delay rates that result in 48.8 kHz resolution.

The MAC, by the way, is a 1.5 bit autocorrelating digitizer that can sample the telescope IF at a rate of 2 GHz. A digital waveform is generated by comparing adjacent samples of data and representing those that are increasing with time a 1, those that are decreasing with time a –1, and those that remain the same a 0. Bit resolution is dramatically improved by averaging in the time domain, e.g. Average (1+0) = 0.5, Average (1+1+0) = 0.7, etc. The frequency information is obtained by fast Fourier transform of the generated wave. For more detail, see the ARO website: http://aro.as.arizona.edu.

Once the spectrometers (also called "backends") are connected, the operator will start with a calibration scan to establish the T_{sys} and hence temperature scale, then take the first spectral line scan. When finished, it will be recorded under a scan number that the operator will log. Pull the scan up on the computer screen. You will have to "reduce" the data by averaging the two receiver channels together (see Appendix II for commands). It is best that you first look at each channel and see if they agree, and then take the average. You will want to do this separately for the filter bank and MAC data (see Appendix II).

CH_3CN Observations

You will next observe CH_3CN in a dense cloud core. Choose one from the catalog and Catalog Tool. Have the operator tune to the CH_3CN: $J = 6 \rightarrow 5$ frequency at 147.1240 GHz in the upper sideband (USB). You will use this setup (check the ARO website to figure out the MAC resolution):

1) Observing procedure: Position-switching, off position: 30 arcminutes west in azimuth
2) Scan time: 6 minutes
3) Spectrometer Backend Set-up: Use filter banks: 1000/1000 series/series; MAC: 600_2k_2

You may not have to point and focus, depending on the time elapsed from the last pointing/focus and the position of the new source on the sky. Your spectra should show "K-components" with spacings of 1:3:5:7:9..., characteristic of a symmetric top. Take a few scans such that you can readily measure the intensities of the six K-components.

HC_3N Observations

Have the operator tune to a transition frequency for HC_3N in the 86-175 GHz range. You will stay on the same source as for CH_3CN. Take several scans, average them together, and tune to the next transition. You should do at least 3 transitions.

Examine your data. Do you have sufficient signal-to-noise to see the HC_3N line, and then measure its intensity accurately? If not, take a few more scans and average them. Make a hardcopy of each spectrum for analysis. Removing a first order baseline from your final spectrum would be useful. You should also fit a Gaussian profile to each spectrum to determine the intensity and line width.

When one transition has been successfully measured, continue with the next one. Take data on as many transitions as you have time for at 2 and 3 mm (86-175 GHz). The operator will have to retune for each frequency.

SiO Observations

Next have the operator tune to the v = 0, J = 2 → 1 transition of SiO at 86.84696 GHz LSB. You will be observing either Chi Cyg, R Leo, or R Cas. Take two scans on the source.

You will use this setup for SiO:

1) Observing procedure: Beam-switching, offset +/- 2 arcminutes
2) Scan time: 6 minutes
3) Spectrometer Backend Set-up: Use filter banks: 250/500; parallel/parallel: MAC: 150_8k_2

Beam-switching is another observing technique to eliminate the background. Instead of moving the telescope, the sub-reflector is nutated on and off source. You can see it moving. You cannot move the sub-reflector too much, or the telescope will be defocused. Therefore, beam-switching can only be used for confined sources.

Next have the operator tune to the v = 1, J = 2 → 1 transition of SiO at 86.24337 GHz LSB. Take one scan on the source. Note the intensity of the signals. Look at each polarization separately.

CO Observations

Have the operator tune to the CO: J = 1 → 0 frequency at 115,271.204 MHz. Repeat the pointing and focusing procedure as previously described. Go to a dense molecular cloud. Tell the operator you want to do a 3 by 3 map of the source with a grid spacing of 60″. The telescope will then take data at 9 positions around the center position. The intensity and line width of the CO emission will change for each position.

The setup for the map is:

1) Observing procedure: Position-switching map, off position: 30 arcminutes west in azimuth
2) Scan time: 1 minutes
3) Spectrometer Backend Set-up: Use filter banks: 1000/1000 series/series; MAC: 600_2k_2

Then take 2 scans on a cold, dark cloud of choice with this setup:

4) Observing procedure: Position-switching, off position: 30 arcminutes west in azimuth
5) Scan time: 6 minutes
6) Spectrometer Backend Set-up: Use filter banks: 100/250 parallel/parallel; MAC: 150_8k_2

Note the difference in line shape between the two sources. Why do they change ?

Next move to an external galaxy and take 4 scans on the galaxy with the following setup. Why is there a large V_{LSR} and line width in this case ?

1) Observing procedure: Position-switching, off position: 30 arcminutes west in azimuth
2) Scan time: 6 minutes
3) Spectrometer Backend Set-up: Use filter banks: 2000/2000; series/series: MAC: 600_2k_2

Then take 2 scans towards Chi Cyg, R Leo, or R Cas. Use the following setup:

1) Observing procedure: Beam-switching, offset +/- 2 arcminutes
2) Scan time: 6 minutes
3) Spectrometer Backend Set-up: Use filter banks: 1000/1000 series/series; MAC: 600_2k_2

Note the intensities and line widths of the CO emission features. Have the operator tune to 110.201350 GHz for ^{13}CO. Take 6 scans towards the star using the previous setup, and note the intensity. What do these data tell you about the ^{12}C/^{13}C ratio ? Make hard copies of all final spectra.

Survey Observations

Go to IRC+40540, CIT6, or CRL2688. Have the operator tune to 93.000000 GHz. Use the following setup:

4) Observing procedure: Beam-switching, offset +/- 2 arcminutes
5) Scan time: 6 minutes
6) Spectrometer Backend Set-up: Use filter banks: 2000/2000 series/series; MAC: 600_2k_2

Take enough data to reach a 5 mK 1 sigma rms noise level, about 1-2 hours. The Unipops command *tsys* will give you this noise level. Halfway through the integration, shift the frequency by 10 MHz (LO shift), you will have to average the two frequencies together using the FSHIFT SHIFT ACCUM commands (see Appendix II and Unipops manual). After this noise level is reached, have the operator tune to 93.5000000 GHz, and repeat the same procedure at this higher frequency. Continue this survey at higher frequencies, stepping in frequency by 500 MHz or 0.5 GHz each time, until the observing time ends.

II. Analysis

1. HCN

a) From the spectra calculate the hyperfine intensity ratios for the source. Use the spectral line equation of transfer to calculate τ, the optical depth:

$$T_L = T_{ex}\,(1-e^{-\tau}).$$

b) Estimate the quadrupole coupling constant, eQq, for HCN from the data. The following formulas will be useful:

$$E(I,J,F) = -eQq\frac{\frac{3}{4}C(C+1)-I(I+1)J(J+1)}{2I(2I-1)(2J-1)(2J+3)}.$$

$$C = F(F+1)-J(J+1)-I(I+1)$$

2. HC_3N

a) Using the HC_3N data to construct a rotational diagram. The following formula will be useful:

$$\log\left(\frac{3kT_L\Delta V_{FWHM}}{8\pi^3\nu S_{ij}\mu_0^2}\right) = \log\left(\frac{N_{tot}}{\zeta_{rot}}\right) - \frac{E_u}{k}\frac{\log e}{T_{rot}}.$$

Here ν is the frequency of the transition, S_{ij} is the line strength, (J + 1) for a linear molecule, μ_0 the permanent electric dipole moment of the molecule (μ_0 = 3.724 D for HC_3N), ζ_{rot} the rotational partition function, and E_u the energy of the upper level for a transition J + 1 → J. The left-hand side of the equation is unit- less and the right-hand side should be in units of K. (1 D = 1×10^{-18} esu cm, 1 esu = $(g\cdot cm^3/s^2)^{1/2}$.) You should get approximately a straight line with a negative slope. From the slope, which equals $-\log e/T_{rot}$, calculate the rotational temperature. The Y-intercept is $\log(N_{tot}/\zeta_{rot})$. From this value, find N_{tot}.

b) Calculate N_{tot} and T_{rot} from the diagram.

3. CH_3CN

a) Use the intensities of the observed K components for CH_3CN to calculate the gas kinetic temperature. Calculate the temperature using all K components, and then with the lowest three components, and the three highest components. The following formula will be useful:

$$\frac{T(K)}{T(K')} = \frac{g(K)}{g(K')}\cdot\frac{J^2-K^2}{J^2-K'^2}\cdot\exp\left(\frac{-E(K)-E(K')}{kT_{Kin}}\right).$$

T(K) and T(K$'$) are the intensities of two K components and g(K) and g(K$'$) are the respective degeneracies. Use 3 for K = 0,3,6,9… and 1 for all other K's. E(K) and E(K$'$) are the energies of the K and K$'$ levels, given by the formula:

$$E(K) = BJ(J+1) - (A-B)K^2.$$

For methyl cyanide, A = 158,099.0 MHz, and B = C = 9,198.83 MHz.

b) Compare the various gas kinetic temperatures calculated. Given the K-components chosen, $T_{Kinetic}$ may vary. Why ?

4. SiO

a) Using the SiO spectra, calculate the vibrational temperature. Explain your result.

b) Given a kinetic temperature of 200 K and assuming the observed temperature of the v = 0 line of SiO, calculate the intensity of the $v = 1, J = 2 \rightarrow 1$ transition for both sources. Why does this differ from your observations?

5. CO

a) Identify any other features in the CO spectrum.

b) From the line widths, estimate the gas kinetic temperature for the observed sources. Why is the line width larger for the external galaxy ? What does the linewidths reflect ?

c) Calculate the $^{12}C/^{13}C$ ratio for the star. Why might this value not be the true ratio in this source? How does this compare to the solar system value? What does this mean for star formation in the local solar neighborhood?

6. Survey

a) From the spectra, identify the emission features observed towards the source. You can find spectral line lists at: http://physics.nist.gov/cgi-bin/micro/table5/start.pl, http://spec.jpl.nasa.gov/, and http://www.ph1.uni-koeln.de/vorhersagen/.

APPENDIX I: Radio Telescopes and Receivers

A radio telescope is basically a large satellite dish with an extremely smooth surface. The Arizona Radio Observatory (ARO) dish is 12 meters in diameter with a surface accuracy to better than 0.1 mm. As shown in Figure 3, the signal from the sky is focused from the "primary reflector," to the "secondary" mirror or "sub-reflector," which in turn directs the signal through an opening in the primary. The signal is then directed by mirrors into the appropriate detectors. Any dish has a limited angular resolution or diffraction limit, meaning that it cannot distinguish two sources of radiation separated on the sky by less than a certain angle θ. A patch of sky whose diameter is $\sim\theta$ is called the beam of a radio telescope, which determines how detailed a mapping it can do. For a telescope diameter D and the observing wavelength λ, the beam diameter is $\theta \cong 1.2\lambda/D$. For your observations, $D = 12$ m and $\lambda = 3$ mm, so $\theta \cong 0.0003$ radians = 62 arcseconds = about 1/30 of the diameter of the Moon = a US quarter seen at a distance of 80 meters = ~angular resolution of the human eye.

The signals from interstellar space are very weak and must be amplified while at the same time minimizing the inevitable addition of instrumental random noise to the signal. The "superheterodyne" technique is used where the signal from the sky is "mixed" (combined) with a "local oscillator" in a device called the "mixer." In this way, the sky signal (at a frequency ν_{sky}, say, of 88 GHz) is converted to a much lower frequency, called the "intermediate frequency" ν_{IF}, where it can be more conveniently and accurately handled. The mixer generates the intermediate frequency ν_{IF} by the sky signal with the local oscillator (at a frequency ν_{LO}), which is mathematically equivalent to producing sums and differences of all incoming frequencies. This intermediate frequency is then immediately sent to a low-noise amplifier constructed such that only a certain range of frequencies (a certain bandwidth) is amplified. For the ARO receivers, $\nu_{IF} = 1.5$ GHz 2mm and 6.3 GHz for the ALMA Band 3 with a bandwidth of 1.0 GHz centered on that frequency.

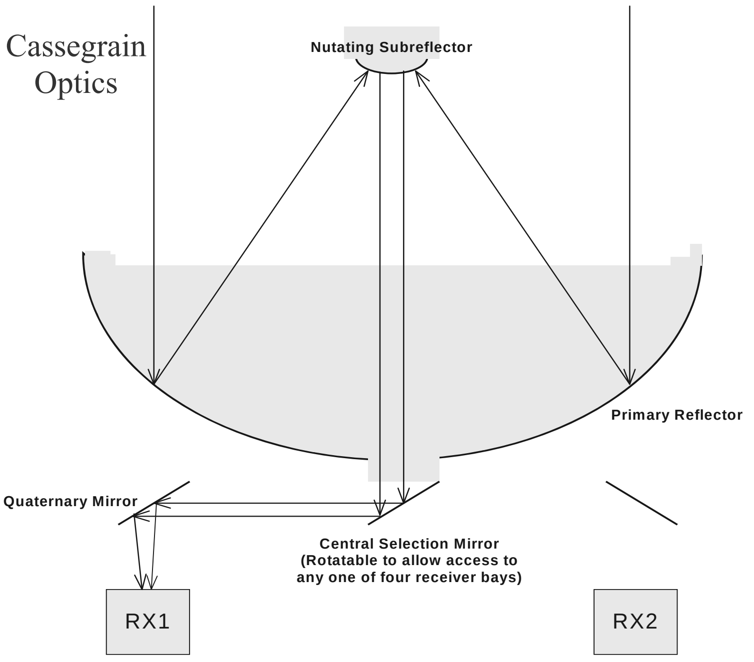


Figure 3: Basic optics of the 12 m radio telescope leading to the heterodyne detector system.

The use of the mixer and amplifier combination thus determines which sky frequency is observed. In practice at ARO, one chooses a value of ν_{LO} ("sets the LO) to get the desired sky frequency according to:

$$\nu_{LO} = \nu_{sky} - 1.5 \text{ GHz}. \tag{2}$$

or

$$\nu_{LO} = \nu_{sky} - 6.3 \text{ GHz}. \tag{2}$$

The local oscillator must maintain a very stable frequency because any drifting with time would cause the sky frequency also to change. Thus before observing begins, the telescope operator will stabilize the LO frequency (to about 1 part in 10^9) using a "phase-lock loop," as well as set the LO to the desired frequency.

The IF signal is next sent a spectrometer, which divides the signal of bandwidth 1.0 GHz into a large number (say 256) of spectral frequency channels (a "filter bank"), each at a different frequency. Numerous spectra resolutions are available. Note that a complete spectrum is obtained at once, without having to take the time to consecutively scan to different frequencies.

The signals from the spectrometer are subsequently sent to a computer disk. In order to reduce the noise in a measurement (i.e. increase the signal-to-noise ratio) data is collected, or "signal-averaged," usually over a 6 minute integration period. These 6 minute "scans" are recorded to the disk under a unique scan number, which is used as an identifier for the subsequent data reduction that you will be doing. Because the stability of the electronics is excellent, one can in turn average a large number of scans to obtain one spectrum with much improved signals from two completely independent sets of receiver electronics. This duplication allows, for other types of observations, the polarization of signals to be measured, but for most observations it gives a 2-for-1 deal and nicely improves our signal-to-noise ratio.

The noise level (T_{rms}) of any measurement, which we want to minimize, follows the radiometer equation:

$$T_{rms}(1\sigma) = \frac{2T_{sys}}{\sqrt{B_W \tau}}, \tag{3}$$

where B_W is the bandwidth (or spectral resolution) of the individual channels of the spectrometer, τ is the integration time, and T_{sys} is the "system temperature," a measure of the power from the electronics and the sky that competes with the desired signal power. The intensity scale in radio astronomy is often expressed in temperature units (Kelvin), a so-called *antenna temperature*, but beware: this temperature often has little to do with any physical temperature being measured. It is rather a measure (through a thermodynamic relation) of the incident energy flux (joules/sec/Hz-of-bandwidth) falling on the antenna in the direction in which it is pointed.

The system temperature can vary with time because sky conditions change with source elevation above the horizon and with weather. Typically, T_{sys} is therefore measured before every scan or every other scan with a "cal scan." Recorded signals are actually voltages, and the cal scan determines the voltage-to-temperature conversion scale by recording the voltage of the system while looking at two known signals: a “load” at ambient temperature and blank sky position, which exhibits a colder temperature.

Another basic observing technique to correct for instrumental errors, especially those affecting the baseline (or zero level) of the spectra, is position-switching or beam-switching. In position-switching, to remove electronic and sky instabilities, scans are actually composed of the average difference between signals taken with the dish pointed “on-source” and then pointed “off-source,” going back and forth at ~30-second intervals. Beam-switching is similar, however, in addition to moving the dish between on- and off-source positions, the sub-reflector also “nutates” or wobbles back and forth. This technique can be used for point sources, such as stars, while position-switching is needed for large objects, such as molecular clouds.

Two other techniques are important at the telescope: “pointing” and “focusing.” The surface of the dish is precise, but nevertheless suffers from gravitational deformations, especially as it tilts for over from the straight-up, “bird-bath” position. These deformations both de-focus the telescope, as well as cause it to aim (point) incorrectly. The pointing calibration is accomplished by observing a strong source of known position (such as a planet or continuum source), which then generates small, real-time corrections so that the telescope physically points at the desired coordinates in the sky. “Focusing” simply consists of moving the sub-reflector slightly in and out to optimize its position for maximum signal strength. Both pointing and focusing will be done during this exercise.

APPENDIX II: Simple commands for data reduction.

UNIPOPS is a data reduction program that was written for use with single dish radio telescope data. The program is capable of reducing most data taken with the KP12m telescope to its final format immediately at the telescope site. Spectral line telescope data is generally reduced to a Cartesian plot of frequency offset (MHz) vs. intensity (K). The frequency offset is relative to the rest frame of the molecule where all Doppler shifts have been accounted for in the operating software. In general, the data acquisition and reduction occurs as an interactive process of: (i) a calibration scan is taken, (ii) a short (about 6 minute) data scan is taken and written to the hard drive, (iii) the data is accumulated and averaged using a weighting function, (iv) a baseline is removed if necessary, and (v) steps (i) – (iv) are repeated until the desired signal to noise is achieved.

UNIPOPS is used to retrieve raw KP12m data from the disk and reduce each series of spectral line observations to a single Cartesian plot using a weighted average for each scan. UNIPOPS is able to do this in a number of ways, but we will stick to the absolute basics here. The data are written to the disk, each with its own unique scan number. There is a base scan number and a subscan number. The base scan number is listed sequentially for each observation made. The subscan number is listed as a decimal to the base number and corresponds to the different backends used for the observation. There will be 4 to 6 subscan numbers for this exercise, e.g. 2.01, 2.02, 2.03, 2.04, 2.11 and 2.12 where the 01, 02, 03, and 04 subscans are the filterbanks and the 11 and 12 are the MAC.

A Quick Look at Each Scan

The first thing we will probably want to do is look at the raw data for each individual scan. This is done using the *get* command or the *f* and *s* macros in the following syntax:

```
LineF> get <scan>.<subscan> page show
LineF> <scan> f
LineF> <scan> s
```

To switch between the filterbanks and MAC use the following commands:

```
LineF> hcdata     // changes the prompt to LineH> for MAC data
LineH> fbdata    // changes the prompt to LineF> for filterbank data
```

The get command takes the scan denoted by <scan>.<subscan> and places it into the plotting array—NOTE when using get hcdata and fbdata are not needed. The commands *page* and *show* are added to actually plot the data to the screen. The macros *f* and *s* show the first and second filterbank or MAC channels on the screen with only a single command depending on the current prompt.

Averaging Two or More Scans Together

If you have two or more scans towards the same position on the sky, at the same frequency and same resolution, that data can be averaged together to improve the signal to noise. To do this is relatively easy as long as the scans are taken sequentially.

```
LineF> empty                      // make sure the accumulation array is empty
LineF> a <scan>.<subscan>         // add each scan on a separate line
LineF> cstack                    // macro to average all the data in the array
LineF> C1                        // average data in polarization 1
LineF> C2                        // average data in polarization 2
LineF> Halves                    // average data in polarizations 1 and 2 together, for a single
                                 scan
```

Removing a Baseline and Determining Line Parameters

Usually a polynomial baseline of order a few is needed to determine line parameter information. There are built in macros for each of these in the program:

```
LineF> nfit = <baseline order>   // nfit is the order of the polynomial used in the fit
LineF> bset                      // will prompt you for mouse clicks in up to 16 regions
LineF> bshape bshow              // optional commands to preview how the fit will look
LineF> baseline page show        // removes the baseline and replots the spectrum
```

After a baseline is removed, Gaussian profiles are fit to each feature.

```
LineF> gset              // will prompt you to select the left, center and right of the peaks
LineF> gshow             // calculates the results and plots them on the screen.
```

If the fit does not converge, try setting the adverb *niter* = 1000 and run *gshow* again.

Printing and Exporting Data

To print any graphic shown on the screen use the command *gcopy* and to print the scan information, use the commands *header tcopy*.

Frequency List

^{12}CO

$J = 1 \rightarrow 0$: 115.271202 GHz

^{13}CO

$J = 1 \rightarrow 0$: 110.210350 GHz

SiO

$J = 2 \rightarrow 1$, $v = 0$: 86.846960 GHz
$J = 2 \rightarrow 1$, $v = 1$: 86.243370 GHz

HCN

$J = 1 \rightarrow 0$: 88.631800 GHz

CH_3CN

$J = 8 \rightarrow 7$: 147.124000 GHz

HC_3N

$J = 8 \rightarrow 7$: 72.783822 GHz
$J = 9 \rightarrow 8$: 81.881461 GHz
$J = 10 \rightarrow 9$: 90.979023 GHz
$J = 11 \rightarrow 10$: 100.076392 GHz
$J = 12 \rightarrow 11$: 109.173634 GHz
$J = 15 \rightarrow 14$: 136.464401 GHz
$J = 16 \rightarrow 15$: 145.560946 GHz
$J = 17 \rightarrow 16$: 154.657284 GHz
$J = 18 \rightarrow 17$: 163.753389 GHz
$J = 19 \rightarrow 18$: 172.849300 GHz

For **Cold Dark Clouds**, you will use this setup:

4) Observing procedure: Position-switching, off position: 30 arcminutes west in azimuth
5) Scan time: 6 minutes
6) Spectrometer Backend Set-up: Use filter banks: 100/250 parallel/parallel; MAC: 150_8k_2

For **Dense Molecular Clouds**, you will use this setup:

1) Observing procedure: Position-switching, off position: 30 arcminutes west in azimuth
2) Scan time: 6 minutes
3) Spectrometer Backend Set-up: Use filter banks: 1000/1000 series/series; MAC: 150_8k_2

For **Oxygen-rich Stars (SiO Maser Sources)**, you will use this setup:

1) Observing procedure: Beam-switching, offset +/- 2 arcminutes
2) Scan time: 6 minutes
3) Spectrometer Backend Set-up: Use filter banks: 250/500 parallel/parallel; MAC: 150_8k_2

For **External Galaxies**, you will use this setup:

1) Observing procedure: Position-switching, off position: 30 arcminutes west in azimuth
2) Scan time: 6 minutes
3) Spectrometer Backend Set-up: Use filter banks: 2000/2000 series/series; MAC: 600_2k_2

For **Carbon-rich Stars (Line Survey Sources)**, you will use this setup:

7) Observing procedure: Beam-switching, offset +/- 2 arcminutes
8) Scan time: 6 minutes
9) Spectrometer Backend Set-up: Use filter banks: 2000/2000 series/series; MAC: 600_2k_2