**Astron. 522**
**Homework Set 4**
**Fall 2006**

## I.      Observations

This homework exercise will focus on measuring spectra of four different interstellar molecules, HCN, $CH_3CN$, $HC_3N$, and SiO, towards several sources L673, W51M, CRL 2688, M17, and Chi Cyg.

HCN:  Here the $J = 1 \rightarrow 0$ transition near 88 GHz will be observed in L673 and M17-NW.  L673 is a cold, dense, dark cloud with a kinetic temperature of ~10 K.  M17 is part of a large, hot HII region associated with massive stars.  These spectra will exhibit hyperfine splittings due to the N nucleus, and thus three emission features will be observed.  The ratio of these lines will be used to examine the physical environment in these clouds, either LTE or non-LTE conditions.

$CH_3CN$:  In this case, the $J = 8 \rightarrow 7$ transition will be observed near 147 GHz towards W51M, a region of young star formation.  This molecule is more complicated than HCN, a linear molecule.  $CH_3CN$ 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 $J = 8 \rightarrow 7$ transition actually consists of many 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 $CH_3CN$.

$HC_3N$:  Here multiple rotational transitions will be observed over 2 and 3mm towards W51M and one transition will be detected in the late-type star CRL 2688.  The observations in W51M will be used to construct a "rotational diagram" from which a molecular "column density" can be extracted, as well as the temperature of the gas-phase $HC_3N$.  Comparison of the emission feature from one transition in W51M and CRL 2688 will demonstrate the differences in the line shape, and hence gas kinematics, between a molecular cloud and a circumstellar envelope.

SiO:  Here the $v = 0$, $J = 2 \rightarrow 1$ and $v = 1$, $J = 2 \rightarrow 1$ transitions near 86 GHz will be observed in the star Chi Cyg.  The spectra of the $v = 1$ transition will show maser emission, which can exhibit differences in the polarization of the emission.  This transition is from the first excited vibrational state, which is ~1800 K above the ground state.  Hence, without the maser action near the surface of the star, this transition would probably not be detectable.

**Pre-observation Calculations**

Calculate all the rotational transitions of $HC_3N$ in the range 65 – 170 GHz.  This range is that covered by the ARO receivers (although there are atmospheric lines of $O_2$ that prevent observations near 118 GHz).  The rotational constants are:

$$B = 4549.058 \text{ MHz}$$
$$D = 0.5439 \text{ kHz}$$

## Observing Procedure

You will begin your observing session by logging into the telescope's observing computer remotely through the internet. This procedure will be demonstrated.

### HCN Observations

The session will begin with observations of HCN. Ask the telescope operator to tune to the HCN: $J = 1 \rightarrow 0$ frequency at 88.6318 GHz. The operator will tune the local oscillator and radio receiver to this frequency. The operator may ask what source you are observing. The source and 1950.0 coordinates are:

$$L673 \ (V_{LSR} = 7.0 \ km/s) \qquad\qquad \alpha = 19^h \ 18^m \ 33.0^s$$
$$\delta = 11^\circ \ 07' \ 30''$$

This source can be found in the XRC.CAT catalog of sources at the telescope. The $V_{LSR}$ is the Doppler correction for this source relative to Earth. It is called "velocity with respect to the Local Standard of Rest," hence $V_{LSR}$. 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. Ask the operator to go to DR-21, a small, strong continuum source. 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
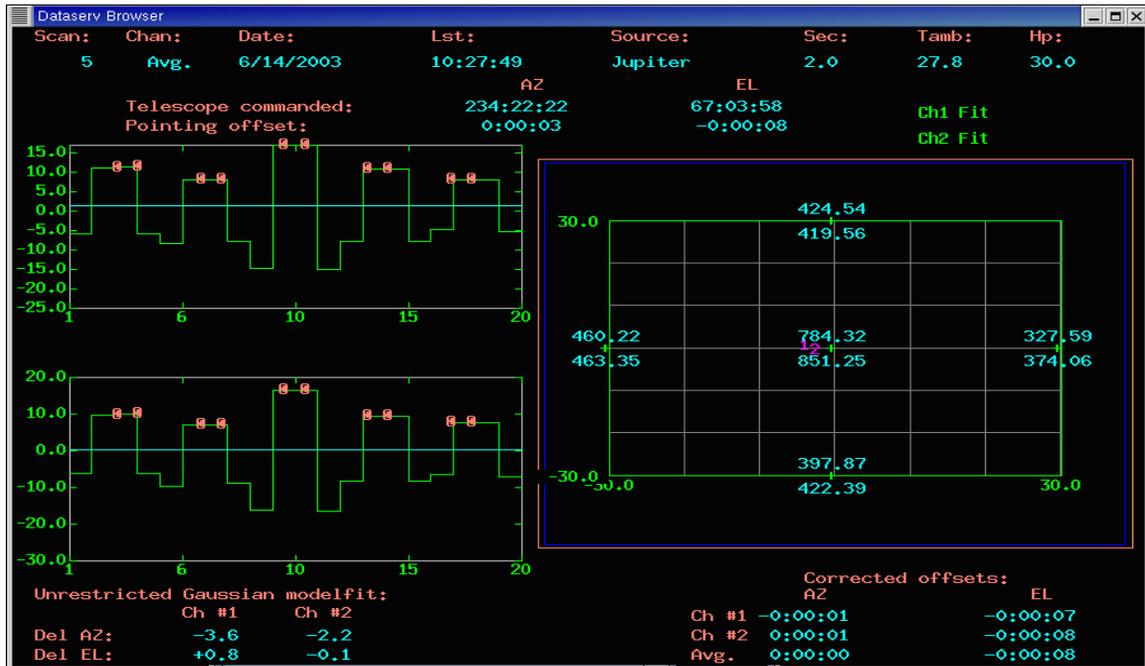


Figure 6: A pointing "5-point" scan displayed in "Dataserve."
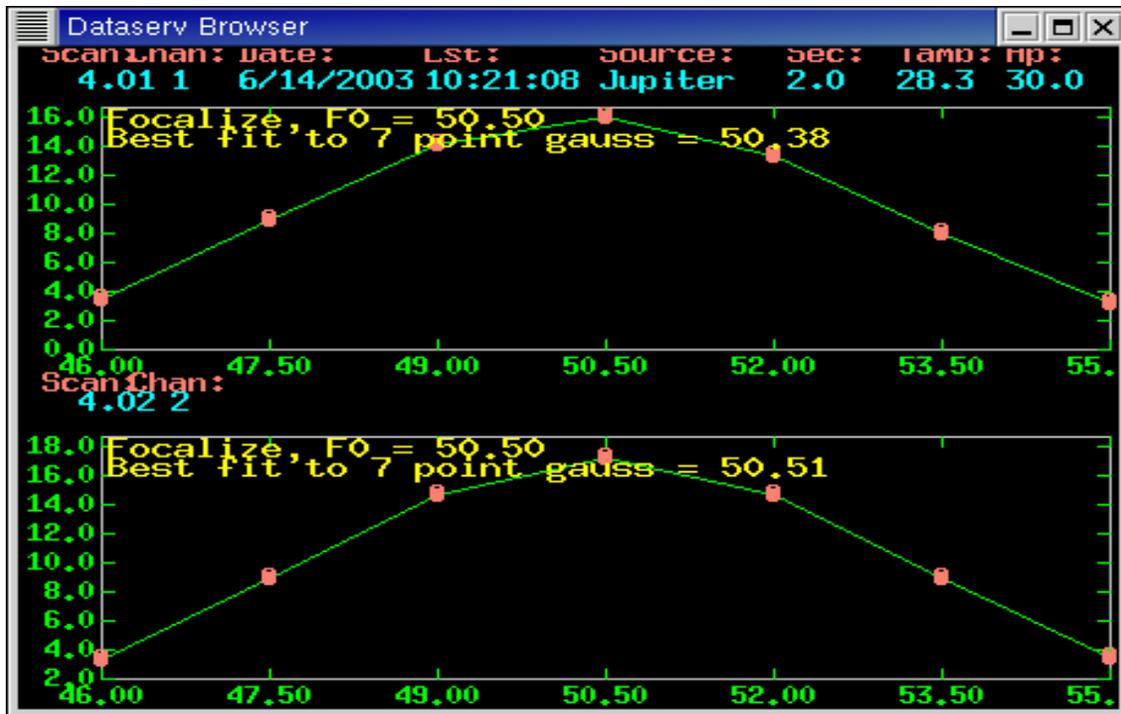
Figure 7: A "focus" scan which shows planet intensity as a function of focus positions.

measured as well as pointing corrections in azimuth and elevation, see Figure 6. 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 computer will take the data and produce a plot of focus versus intensity. The curve will increase to a maximum and decrease, see Figure 7. 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 measure an off-position set in azimuth. The spectrometer set-up places each receiver channel into a 100 kHz and 250 kHz filter bank (2 by 128 channels each)

and splits the Millimeter AutoCorrelator (MAC) in half for each channel. The MAC 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 (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).

You will need to signal-average or integrate on this source for about half an hour (about 3 scans) to see data with a good signal-to-noise ratio. Once this is achieved, you will move to M17-NW. Take 2 scans on this source and compare the data from the two sources.

M17-NW ($V_{LSR}$ = 19.0 km/s)          $\alpha = 18^h\ 17^m\ 19.0^s$
                                        $\delta = -16^o\ 13'\ 01''$

## CH$_3$CN Observations

You will next observe CH$_3$CN in W51M. The coordinates of this source are:

W51M ($V_{LSR}$ = 57.0 km/s)           $\alpha = 19^h\ 21^m\ 26.2^s$
                                        $\delta = 14^o\ 24'\ 43''$

Have the operator tune to the CH$_3$CN: $J = 8 \rightarrow 7$ frequency at 147.1240 GHz. 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: 600_2k_2

You will not have to point and focus. You should see multiple lines called "K-components" with spacings of 1:3:5:7:9... This pattern is characteristic of a symmetric top. Take two scans such that you can readily measure the intensities of at least six K-components.

## HC$_3$N Observations

Next have the operator tune to a frequency that you calculated for HC$_3$N in the 130-170 GHz range. You will stay on W51M for these scans.

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.  Take 2 scans per $HC_3N$ frequency.  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 one $HC_3N$ line at 2 mm (130-170 GHz), one $HC_3N$ line at 3 mm (90-115 GHz),  then one in the 3 mm region from 65 to 90 GHz.  The operator will have to retune for each frequency.

After you have sufficient data on W51M, you will change sources, and point the telescope towards CRL 2688 with the coordinates:

CRL 2688 ($V_{LSR}$ = -33.3 km/s)        $\alpha = 21^h\ 00^m\ 20.0^s$
                                                                          $\delta = 36^o\ 29'\ 44''$

You will use this setup for CRL 2688:
1) <u>Observing procedure</u>:  Beam-switching, offset +/- 2 arcminutes
2) <u>Scan time</u>:  6 minutes
3) <u>Spectrometer Backend Set-up</u>:  Use filter banks: 1000/1000; series/series:  MAC: 600_2k_2

Take two scans of $HC_3N$ towards this source.  Compare the line shapes.

<u>SiO Observations</u>

Next have the operator tune to the v = 0, J = 2 $\rightarrow$ 1 transition of SiO at 86.84696 GHz.  You will be observing the source Chi Cyg.  Take two scans on the source.

Chi Cyg ($V_{LSR}$ = 9.5 km/s)          $\alpha = 19^h\ 48^m\ 38.5^s$
                                                                   $\delta = 32^o\ 47'\ 10''$

You will use this setup for SiO in both sources:
1) <u>Observing procedure</u>:  Beam-switching, offset +/- 2 arcminutes
2) <u>Scan time</u>:  6 minutes
3) <u>Spectrometer Backend Set-up</u>:  Use filter banks: 250/500; parallel/parallel:  MAC: 150_8k_2

Next have the operator tune to the v = 1, J = 2 $\rightarrow$ 1 transition of SiO at 86.24337 GHz.  Take one scan on the source.  Note the intensity of the signals.

## II.    Analysis

Please include all spectra with the homework that is handed in.

1. HCN
a)  From the spectra calculate the hyperfine intensity ratios for the two sources.  Which source exhibits significant non-LTE hf ratios?  Why?

b)  Estimate the quadrupole coupling constant, eQq, for HCN from the data.

c)  Calculate the Einstein A coefficient for the $J = 1 \rightarrow 0$ transition of HCN.


2. HC$_3$N
a)  Using the HC$_3$N data for W51M construct a rotational diagram.  The following formula will be useful:

$$\log\left(\frac{3kT_L \Delta V_{FWHM}}{8\pi^3 \nu S_{ij} \mu_0^2}\right) = \log\left(\frac{N_{tot}}{\zeta_{rot}}\right) - \frac{E_u}{k}\frac{\log e}{T_{rot}}. \tag{1}$$

Here $\nu$ is the frequency of the transition, $S_{ij}$ is the line strength, $\mu_0$ the permanent electric dipole moment of the molecule ($\mu_0 = 3.724$ D for HC$_3$N), $\zeta_{rot}$ the rotational partition function, and $E_u$ the energy of the upper level for a transition $J + 1 \rightarrow J$.

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

c)  Calculate the critical density for each of the observed transitions of HC$_3$N, assuming $T_{rot} = T_k$, and a collisional cross-section of $10^{-15}$ cm$^2$.

d)  When do you expect the rotational diagram approach not to work, and why?

e)  Explain the line shapes of W51M and CRL 2688.  Why are they different?


3. CH$_3$CN
a)  Use the intensities of the observed K components for CH$_3$CN 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.

b)  Compare the various gas kinetic temperatures calculated.  Why do the vary?

c)  Compare your results with those of HC$_3$N.  Why do they differ?

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?

**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 5, 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 ~θ 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 λ = 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 $\nu_{sky}$, say, of 88 GHz) is converted to a much lower frequency, called the "intermediate frequency" $\nu_{IF}$, where it can be more conveniently and accurately handled.  The mixer generates the intermediate frequency $\nu_{IF}$ by the sky signal with the local oscillator (at a frequency $\nu_{LO}$), 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 with a bandwidth of 1.0 GHz centered on that frequency.
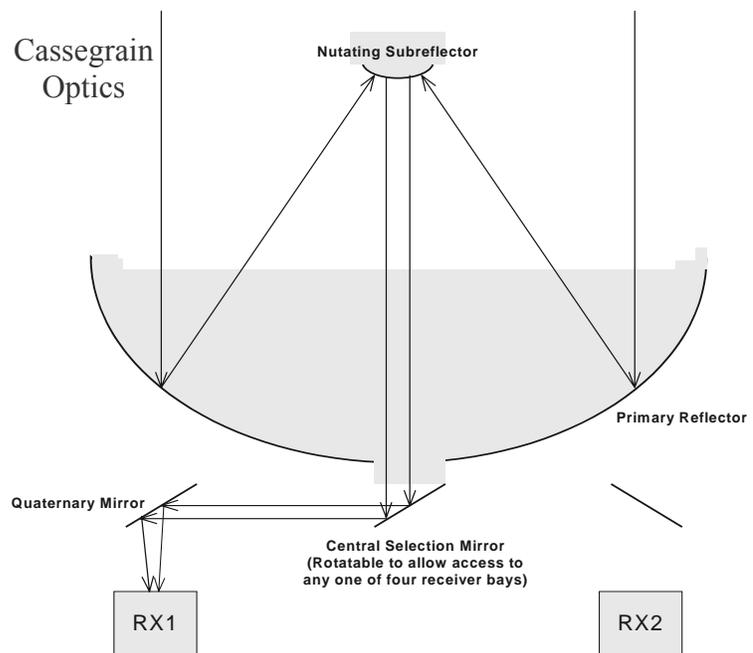


Figure 5:  Basic optics of the 12 m radio telescope leading to the heterodyne detector system.

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

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

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, $\tau$ 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

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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

*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*.