21-cm LINE ASTRONOMY WITH A SSB MIXER

This week we will measure the 21-m line (colloquially known among astronomers as the *HI*—that's *H - "Roman numeral I", pronounced "H-one"*) line shape, velocity, and intensity using the big horn on Campbell's roof. Most of the measured power comes from our own electronics, not the HI line. It's often called "noise". We need to get rid of this instrumental contribution. We need to get our *intensities properly calibrated* and the *Doppler correction properly applied.* To this end, we want all groups to observe the same position on the sky to see if they get the same answer (This has never happened before in the history of this course!). We want *each group* to do the measurements and *each individual* to do the reduction.

Plots are due April 12 in class!!!

1. The Measurements

Begin by getting the data! Before beginning measurements in earnest, it's important to make sure the signal levels are OK and to experimentally determine which way frequency increases on your power spectra. So before getting out there in the rain to point the horn:

1. Set the system up as you will be using it to observe. Take some data. How fast must you sample? Remember that our low-pass filter has a $\sim$ 2 MHz cutoff frequency. What sample mode should you use for SSB sampling?

   We recommend using the "integer" keyword for the sampler, which returns integer numbers instead of voltages; this is faster. If you do this you'll have to subtract the mean to get rid of the d.c. offset before taking Fourier transforms. In fact, it doesn't hurt to always do this, because there is usually an extraneous d.c. offset from imperfections of various sorts.

2. Look at the range of sample values by plotting a bunch of them. (If you have enough time, you could try using the `histogram` function for this). The sampled numbers should cover plenty of bits; quantization should be only barely, or not at all, visibly evident in the histogram.

3. Insert a test signal so that it appears in the upper sideband and take some data; then change the test signal frequency so it's in the lower sideband. You'll use this to determine whether the frequency axis is flipped or not.

Having determined that the system works, it's time to do astronomy! Point the horn to Galactic coordinates $(l, b) = (120°, 0°)$. The rotation matrix for converston between equatorial and Galactic coordinates is in the coordinate-conversion handout. We'll take three separate measurements. Take plenty of samples—the more you take, the higher the signal-to-noise ratio. Call this number

NSAMP; you'll calculate the power spectrum from these[1].

1. Set the first local oscillator so that the HI line is roughly centered in the baseband spectrum. (The HI line frequency is 1420.4058 MHz). Because this is centered on the line, call this spectrum s_{online}.

2. Displace the first l.o. so that the line falls outside of the baseband spectrum. Because this is centered off the line, call this spectrum $s_{offline}$.

3. Repeat the offline spectrum with the cal on; call this one $s_{offline,calon}$.

2. The Analysis

For the reduction:

1. Make a plot or a histogram[2] of some representative voltage values in one of your three datasets to make sure that they are, indeed, not too quantized and don't exceed the maximum range of the ADC. The histogram shape should look like a well-known function. Which function? Does it?

2. Make power spectra of the three measurements. These spectra will look EXTREMELY NOISY! And they will have a number of points equal to the number of samples. Thus, the resolution (separation between adjacent channels on the power spectrum) will be the total bandwidth divided by NSAMP[3]. This is much narrower than needed. No HI line with a width of less than 6 kHz has ever been detected, and for our purposes a resolution of 10 KHz is plenty good enough.

   You can smooth over channels and reduce the noise. For example, suppose you want to reduce the the NSAMP channels in the power spectrum *pspect* to 512 channels. In IDL there are two easy ways to do this:

   (a) Use IDL's `smooth` function: `newspect = smooth(pspect, NSAMP/512)`. This degrades the resolution, but you will still have NSAMP channels in the output spectrum.

   (b) Use IDL's `rebin` function: `newspect = rebin(pspect, 512)`. This degrades the resolution and gives you 512 channels channels in the output spectrum.

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[1] To get really good signal-to-noise, take lots (100?) of power spectra and average them

[2] To make a histogram, you can use IDL's native `histogram.pro` or one of our wrappers: the simpler one `histo_wrap.pro` or the more general `hist.pro` .

[3] By the way, what is the total bandwidth: is it the sampling frequency or half the sampling frequency? Remember—your input numbers are complex. . .

In the smoothed s_{online} spectrum you should be able to see the HI line—together with the instrumental bandpass, and perhaps some other bumps. The instrumental bandpass is determined mainly by the low-pass filter, which should fall smoothly to zero as the frequency increases. Does it?

3. You can remove the instrumental bandpass, and thus get the shape of the line (but not the intensity), by taking the ratio

$$ratio = \frac{s_{online}}{s_{offline}} \ . \tag{1}$$

This is the *first* factor (i.e., the shape) in equation (13) in the spectral-line handout.

4. To get the line intensity in terms of the calibration noise source, multiply the ratio spectrum by T_{sys}—the second factor in equation (13). We obtain T_{sys} by combining the calon and caloff spectra, as per equation (15) in the handout:

$$T_{sys} = \frac{\sum s_{offline}}{\sum (s_{offline,calon} - s_{offline})} T_{cal} \tag{2}$$

where the numerator and denominator are summed over all of the channels, as in equation (15). We think T_{cal} is about 20 K. Then the final, intensity-calibrated spectrum is equation (16) in the handout, namely

$$final\ calibrated\ spectrum = ratio \times T_{sys} \tag{3}$$

5. Plot your final spectrum versus the r.f. frequency.

6. Plot your final spectrum versus the Doppler velocity[4]. Remember that, by astronomical convention, positive velocity means motion away (remember the expansion of the Universe!), so

$$\frac{v}{c} = -\frac{\Delta f}{f_0} \ , \tag{4}$$

where c is the speed of light and Δf is the frequency offset from the line frequency f_0[5].

7. Calculate the Doppler correction using the `ugdoppler.pro` (for documentation use `doc` or `doc_library`). Correct the velocities to the Local Standard of Rest (LSR) and make a third plot.

Notes on `ugdoppler`:

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[4] Astronomers usually express velocities in km s^{-1}.

[5] Radio astronomers, being frequency-oriented, use this equation; optical astronomers, of course, use something different: $\frac{v}{c} = \frac{\Delta\lambda}{\lambda_0}$.

(a) You need the Julian day of the observation, which you get from IDL's `JULDAY` function. The Julian day is defined for *Greenwich*, whose time is 8 hours ahead of PST (and 7 hours ahead of PDT!). That is, if the time in Berkeley is 6 pm (that's 18 hours) on March 17, then the time in Greenwich is 1 hour on March 18, and that's what you use as input to `JULDAY`. To obtain the Julian day right now, use `systime( /julian, /ut)`.

(b) You need the observatory coordinates (north latitude and west longitude) in degrees; you could enter them with the pair of optional input parameters `(nlat, wlong)`, but you don't have to because the default values are Campbell Hall's values.

Hand in the plots together with relevant commentary.