In this lab, you will use a small antenna to measure the neutral hydrogen in our Galaxy.

The lab is set up so that each group will measure a small part of the Galaxy, then for a final project possibility, we will stitch the different observations together into one big map.

Your aim in this project is to obtain the data for an assigned part of the sky. In this lab, you will obtain and calibrate the data.

As a final project, some of you will analyze the data to determine the velocity of the Galactic neutral hydrogen at two positions. From this measurement, and the added information that the sun is 8000 parsecs from the Galactic center, you will measure the Galaxy's mass.

You will check out the tools described in Section 1.

You will do a formal writeup. The writeup should consist of the following sections:

1. Introduction (5%): Describe the purpose of the lab & background
2. Procedure (55%): Describe the setup of the hardware and the data taking process
3. Data Analysis (25%): Report and analyze your measurements
4. Data Packaging and Delivery (10%): Put the data together and turn them in with appropriate metadata
5. Conclusions (5%): Summarize what you learned

1 Setup and Tools

1.1 Plan your observations

You will observe at least three sky locations for at least 5 minutes each.

If you have a stable, sheltered observing location in which you can keep the laptop indoors and guaranteed dry and the telescope outdoors and pointing at the sky, you will do a 24-hour *drift scan*.

If you do not have such an observing location, instead, find out what time of day (or night) the Galaxy will pass high enough to be observable from your location. Depending on your observing site, that might be a fairly narrow time range.

Determine what parts of the Galaxy you will look at and how. Point as close to the Galactic center as you can without hitting trees or other obstructions, then step up in altitude in 10 degrees until you hit the opposite effective horizon. At each altitude, note what Galactic latitude and longitude you will be looking at, and note at which azimuthal angle you will be looking. Azimuthal angle is defined as degrees from North measured clockwise.

1.2 Get the Tools

You will need to check out the following items to use for the observations.

These are stored in the Bryant Space Science Center (the astronomy department) in 1b, which is attached to Room 3.

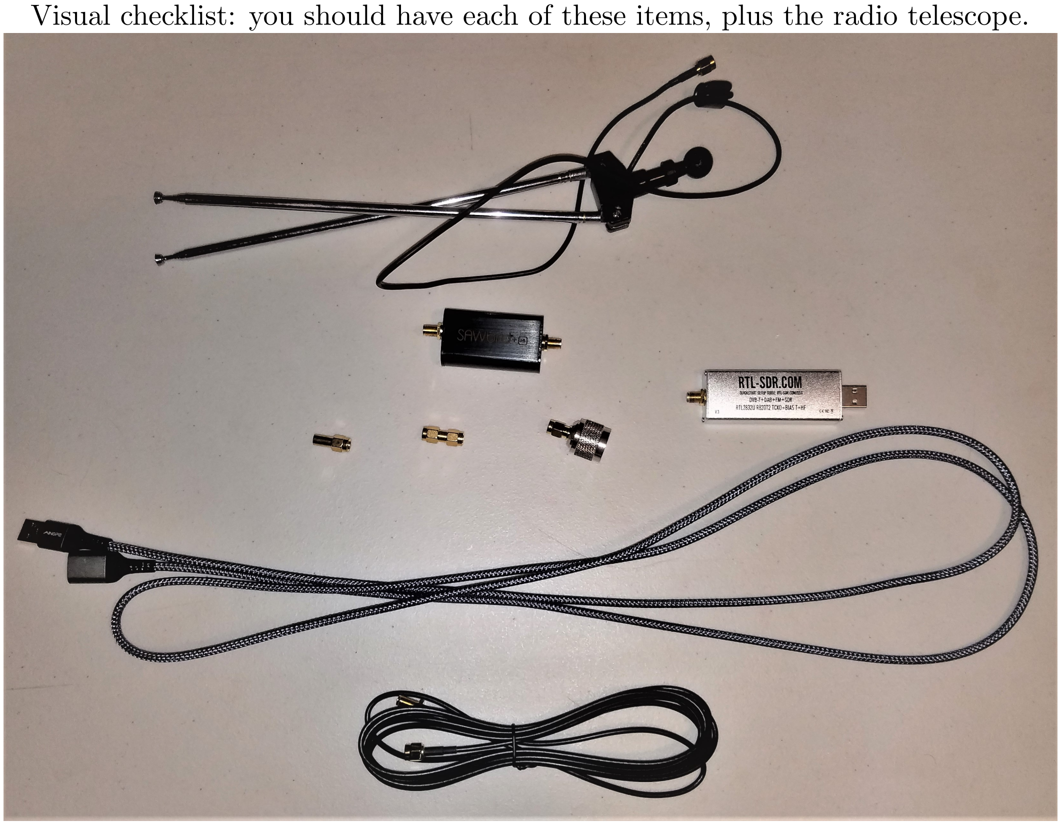
If you are using the telescopes at your home or an off-campus location, you will need to pick up the equipment. If you have a car, you should drive to campus and pull up close to the building (there is a loading dock in back you can park at for up to ten minutes, but I can't guarantee anything about parking enforcement - maybe leave your 4-way flashers on and put a note in your windshield), collect the materials, and leave as quickly as possible. If you are trying to complete Part 2 of the Site Characterization lab, *plan it out in advance*! The work you need to do to characterize the site can be completed in about 10 minutes *if* you come with a plan, but it could take much longer if you're unprepared! I don't want anyone getting a ticket.

If you *do not* have a car, you can do parts 1.3-1.5.3 with materials that will easily fit into a backpack, i.e., everything except the Radio Telescope. You will need to do the observational part of the lab on campus at Bryant Space Science Center or at the Campus Teaching Observatory (outside).

1.2.1 Materials list

- Radio Telescope, including: dish, mounting structure, tripod, feed
- Simple dipole antenna ("rabbit ears")
- RTL-SDR (RealTek Software-Defined Radio) USB (Universal Serial Bus) dongle
- LNA (Low-Noise Amplifier)
- Coaxial Adapter (big to little)
- Coaxial Adapter (male-to-male, little-to-little)
- Coaxial cable
- 50-ohm terminator
- Observing laptop
- Power cord for laptop
- USB extension cord

Visual checklist: you should have each of these items, plus the radio telescope.



You will also need a tool to measure the altitude and azimuth of your antenna. Your phone can serve both purposes with appropriate apps installed. Otherwise, you need a compass, a protractor, and a level.

1.3 Set up computer

Boot up the computer, load up an anaconda session (either notebook or terminal, up to you), and make a directory with your name on it. You will likely want to use several different subdirectories to store the test data and the science data, but you'll need to ensure the right scripts are present in each directory.

Open either Jupyter Notebook (.ipynb), an Anaconda terminal session, or a Spyder session to create a python work space to follow the lab instructions. Go to the github link listed in the lab (`https://github.com/keflavich/RTL_SDR_HI_Observations`). Download and extract the files from there onto your machine. You will want to copy the `run_an_integration.py` and `scan_calibrator_signals.py` to the folder you created in step 1.

In the python session, run the command:
`import rtlsdr` If this works, there will be no message. If you get an error message, then run the script `install_rtlsdr.py` from the github repository:
`%run install_rtlsdr.py`

Because those two python files are now in the same folder as your working python file, you can then do the following to access the functions of either python file:

```
>>> from run_an_integration import record_integration
>>> record_integration(...)
```

(you will need to replace the `...` with appropriate arguments)

To get more information about the functions you can type in the terminal: `>>> record_integration?`

Upon completing the lab, you can zip up the contents of your folder and send it to your preferred storage location (e.g., dropbox or google drive).

1.4 Test the software and connections

The software you need for this project is at `https://github.com/keflavich/RTL_SDR_HI_Observations`, but it should already be installed on the laptop you checked out. Specifically, you'll need to `import` the `record_integration` function from `run_an_integration.py`:
`from run_an_integration import record_integration`

Load up the software and run the `bias_tee_on.bat` script. You can do this within python by running the commands:
`import subprocess`
`response = subprocess.call([r'C:\Users\USERNAME\Anaconda3\Library\bin\bias_tee_on.bat'])`
You need to replace `USERNAME` with the username on the computer, probably `student` or `lab-admin`.

NOTE: The `bias_tee_on.bat` script may be in a different location:
`response = subprocess.call([r'C:\ProgramData\Anaconda3\Library\bin\bias_tee_on.bat'])` you need to specify `anaconda_path='C:\ProgramData\Anaconda3\'`
or
`anaconda_path='C:\Users\students\Anaconda3\'`

Verify that the indicator light on the LNA turns on. If it does not, see the troubleshooting section (§5).

1.5 Take basic calibration data

Disconnect the SDR dongle from the cable that connects it to the antenna. Put the 50-ohm resistor on the end of the SDR dongle.

Using the integration tool, take a 1-second and a 60-second integration. You will do this using the `record_integration` command. Label these as `50ohm_calibration` scans using the `obs_type` keyword argument. Take five (5) of each of the 1-second calibration scans. Take one (1) 60-second integration for each

The LNA should be connected to the SDR via the long coax cable. The SDR should be plugged in to the USB extension cord and into the computer USB port.

Attach the 50 ohm resistor to the SDR for the basic calibration steps.

configuration (resistor on, resistor off, LNA on with resistor, LNA on without resistor). Set the altitude and azimuth both to -999 to indicate that this is not a real on-sky observation.

Example `record_integration` call:

```
record_integration(altitude=-999, azimuth=-999, tint=1,
                   observatory_longitude=-82.3, observatory_latitude=29.6,
                   obs_type='50ohm_calibration', freqcorr=60)
```

Recall that you can look at the documentation for a function with a `?`, e.g.: `record_integration?`. There are many other keyword arguments that may be needed; see Section 5 below.

If no FITS file is produced and there is an error message, try again. If there is still an error message, then increase the `timeout_factor` by steps of 1 until it does work. The default is 2. Stop before you get to `timeout_factor=10`.

Remove the resistor, then repeat these observations. Label them as `bare_calibration`.

Attach the LNA to the SDR dongle via the coax cable. Take calibration measurements with the 50 ohm resistor attached (`50ohm_calibration_LNA`) and without (`bare_calibration_LNA`).

The LNA should be connected to the coax cable via the male-to-male adapter

1.5.1 Frequency Calibration

Now, attach the dipole antenna to the RTL-SDR. Make sure the LNA is not in the signal path! (the LNA includes filters that will block the NOAA signals) Use the `calibrate_on_noaa` command from the `scan_calibrator_signals.py` script to take a frequency calibration measurement. Record the "Measured Frequency Offset" it reports. Repeat this measurement 10 times. Record each value, then report the mean and standard deviation. This value, rounded to the nearest integer, will be your `freqcorr` (frequency correction) to apply in the observations below.

1.5.2 Plot the calibration data

Now that you've taken some data, plot it!

The SDR should be connected to the bunny-ear dipole antennae for the frequency calibration step.

Using `astropy.table`, read the files. `tbl = astropy.table.Table.read('filename_goes_here.fits')`
Plot the spectra. There are a few different spectra to plot:

- Plot column `power1` on the y-axis against `freq1` on the x-axis
- Plot column `power2` on the y-axis against `freq2` on the x-axis
- Repeat the above steps in different plot windows for each of the four calibration scans. You should end up with a total of 8 plots, one pair for each of the calibration scan types.
- Label each plot by its integration time and whether it had the resistor

Question: (How) do the spectra differ?

1.5.3 Frequency Switching

To obtain clean, calibrated data, we are using a techique called *frequency switching*, in which we record data at two frequencies separated by more than the expected line-width, but less than the receiver bandwidth. In frequency switching, we integrate for two consecutive observations, then take their difference.

Plot `fsw_pow` vs `freq1` for each of the four spectra in a four-panel plot. Use `matplotlib.pyplot.subplot(2, 2, ii)` to make this four-panel plot.

Question: How do these spectra differ from the non-frequency-switched spectra?

1.6 Set up the radio telescope antenna

At your selected site, set up the antenna and observing station.

1. Scout out the location, make sure it's clear
2. Set up the tripod

3. Put the mount in the tripod
4. Attach the dish to the mount
5. Point the dish straight up, then tighten the altitude-locking screws
6. Measure how far the feed is off of zenith. If it's more than a degree off of vertical, adjust it and re-measure.
7. Set up your observing station (your computer and SDR)
8. Connect the LNA to the antenna feed using the big-to-little adapter (the side with the micro-USB port should be pointed toward the antenna feed)
9. Connect the coax cable to the LNA
10. Connect the other end of the coax cable to the RTL-SDR via the little-to-little adapter
11. Turn on the computer
12. Plug the dongle into the USB extension cord
13. Plug the USB extension cord into the computer

For your writeup, be sure to note: Did you do anything differently from the above? Were there any steps left out of these instructions (it's very possible something important and obvious was left out!).

The LNA should connect to the antenna cable through the large adapter, attached on the side that has a micro-usb-in.

2 Observe your target

Do the observations!

Make sure to keep an observing log for this session. Use a spreadsheet, either google docs or excel.

Observation ID	Observation Time	Altitude	Azimuth	Gal. Longitude	Gal. Latitude	t_{int}	Notes
1							
2							

2.1 Point the telescope at the target

Using the adjustable screws, loosen the altitude mount until it can swing freely - *be sure to hold on to it* so it doesn't fall over! Adjust the antenna to point at the desired altitude. Measure that you're pointing at this altitude using your tool (e.g., your phone app). Record what you measured, and record the time you made the measurement. Once it is pointed at the right altitude, lock in the screws to hold pointing fixed.

Rotate the telescope to point at the correct azimuth. Use a compass; note that the magnetic declination (difference between magnetic and true north) in Florida is about 5°. Remember that azimuth starts from 0° to the north, is 90° to the east, and is 180° to the south. The telescope should easily stay pointed at the appropriate azimuth without any locking mechanisms as long as you don't bump it.

2.2 Obtain an integration

Before you start taking data, make sure your computer's clock is correct.

To record data, remember you need to pass several parameters to the `record_integration` command:

- `freqcorr` should be set to the number you measured in 1.5.1
- `altitude` and `azimuth` must be set to the telescope's alt and az
- The observatory latitude and longitude must be set correctly
- `obstype` should be "science"
- The integration time should be set to 1 minute (60s).

Plot your data. Take notes:

- Did you detect the HI emission line?
- What is the approximate velocity of the HI emission line?
- Is there Radio Frequency Interference (RFI)?

2.3 Observe all your targets

Repeat the steps in §2.1 and 2.2 for each target you have selected.

By the end of this observing session, you should be able to create a data table like this:

Observation ID	Galactic Longitude	Galactic Latitude	Velocity Peak of HI
1	$\ell =??°$	$b =??°$	?? km s^{-1}
2	...	...	...
3	...	...	...

2.4 Observe the Sun

In order to calibrate the antenna, we need to observe the sun. During the day, calculate a position the Sun will pass through. Point the telescope at that position starting *at least* 1 hour before the sun passes through the target position and keep recording for *at least* 1 hour after.

2.5 Data Packaging and Delivery

Once you've acquired data for all of your targets and the corresponding calibration data, you're done observing.

You will need to upload all of the data *and* your observing log. Your log should be in spreadsheet form. If you used google sheets, export the file to excel format on the observing computer.

Before you do, create a `README` file describing the data. Open up notepad.exe, and put in the file:

1. your name
2. the date
3. the number of files
4. the total size of files
5. any notes about mis-labeled files or things that might have gone wrong
6. the name of the observing log file

Then, zip up the files, including the README, the log, the FITS files, and any plots and notebooks you want to save: select all of the files you want to upload in Windows Explorer, right click on them, and select "Send to" → "Compressed (zipped) Folder".

Upload the zip file to canvas. If we run out of space on canvas, we might have to switch to dropbox or onedrive, but we'll start with canvas.

3 Analysis

From your solar observation, determine what the 'gain' factor is. This is your primary calibration term for converting your measurements from arbitrary amplitude into meaningful intensity measurements.

For each of your spectra, determine:

1. Did you detect an HI signal?
2. What was the observed centroid velocity of that signal? Its width? Its amplitude?
3. What is the uncertainty on those measurements?
4. What was the velocity of your observatory in the direction of the signal at the time of observation?
5. What is the observed velocity in the local standard of rest?

4 Writeup

Copied from above, this is the breakdown of the lab writeup:

1. Introduction (5%): Describe the purpose of the lab & background
2. Procedure (55%): Describe the setup of the hardware and the data taking process
3. Data Analysis (25%): Report and analyze your measurements
4. Data Packaging and Delivery (10%): Put the data together and turn them in with appropriate metadata
5. Conclusions (5%): Summarize what you learned

The Procedure section should include your observing log.

The Data Analysis section should include plots of the data. You will likely need to download the zip file you uploaded to canvas so you can include appropriate plots.

5 Troubleshooting

5.1 The LNA light doesn't turn on

Is it plugged in?

Is it pointing the right way? (micro-usb side should face toward the feed, away from the RTL-SDR dongle)

Is the dongle plugged in to USB?
Try the other USB port(s) on the computer. Does it work now?

Try a set of different commands. Each of these might work. Note which one does! There are two different varieties being explored here: one is changing the path to the executable, the other is changing which USB ID is being used.

```
subprocess.call([r'C:\Users\student\Anaconda3\Library\bin\rtl_biast','-b','1','-d','0'])
subprocess.call([r'C:\Users\lab-admin\anaconda3\Library\bin\rtl_biast','-b','1','-d','0'])
subprocess.call([r'C:\Users\student\Anaconda3\Library\bin\rtl_biast','-b','1','-d','1'])
subprocess.call([r'C:\Users\lab-admin\anaconda3\Library\bin\rtl_biast','-b','1','-d','1'])
```

5.2 I get an error when I run `record_integration`

There are many possible errors. If you see a timeout error, try changing `sleep_time_factor`, `timeout_factor`, or `bias_tee_timeout` based on the instructions in the function's docstring (reminder: `record_integration?` will show the docstring).

If you get a USB 12 error, try changing the `device_index` to 1 or 2.

If there is an error but you can't figure out what it is, try setting `verbose=True` to see if you can get some debugging information, and share that with the instructor & TA.

Finally, if the LNA light is on, but you get errors related to the bias tee, try setting `skip_bias_tee=True`. However, you should turn off this feature afterward - you need to turn on the bias tee to have the LNA on!

5.3 No FITS files are appearing when I run record integration

If no FITS files appear when you run the `record_integration` code, try changing `freqcorr` to another value (not zero).